Scholars Academic Journal of Biosciences

Abbreviated Key Title: Sch Acad J Biosci
ISSN 2347-9515 (Print) | ISSN 2321-6883 (Online)
Journal homepage: https://saspublishers.com

NIH National Library of Medicine National Center for Biotechnology Information ACCESS
NLM ID:101629416

Physics

# Advanced Graphene–Mxene Supported MOF-Derived Hybrid Nanomaterials for High-Performance Energy Storage, Supercapacitors, and Hydrogen Evolution Technology

Kalsoom Hayat[1*], Ambar Riaz[2], Aimen Amjad[3], Zubair Aziz[1], Muhammad Naeem Khalid[4], Muhammad Suleman Ahmad[5], Iqra Rizwan[4], Junaid Abbas[6], Mujahid Abbas[4] , Khizra Waheed[5]

[1]Department of Physics, University of Agriculture Faisalabad, Pakistan
[2]Department of Physics, University of Engineering and Technology, Lahore, Pakistan
[3]Department of Chemistry, Forman Christian College (A Chartered University), Pakistan
[4]Institute of Chemical Sciences, Bahauddin Zakaria University, Multan, Pakistan
[5]Institute of Physics, Bahauddin Zakaria University, Multan, Pakistan
[6]Institute of Physics, Ghazi University, Dera Ghazi Khan, Pakistan

**DOI:** https://doi.org/10.36347/sajb.2026.v14i05.001 | **Received:** 05.03.2026 | **Accepted:** 22.04.2026 | **Published:** 04.05.2026

***Corresponding author:** Kalsoom Hayat
Department of Physics, University of Agriculture Faisalabad, Pakistan

**Abstract** | **Original Research Article**

Energy demand is rising across modern systems. Efficient storage and conversion are now critical challenges. This study introduces a novel design based on advanced Graphene–MXene Supported MOF-Derived Hybrid Nanomaterials. The approach integrates conductive graphene layers with MXene sheets and MOF-derived porous structures. Each component plays a precise role. Graphene improves electrical conductivity. MXene enhances surface reactivity. MOF templates create a stable porous network. The combined structure forms a continuous pathway for charge transfer. This design reduces resistance and improves ion diffusion. As a result, electrochemical performance is significantly enhanced. The material shows high capacitance and long cycle stability in supercapacitors. It also demonstrates strong catalytic activity in hydrogen evolution reactions. Structural uniformity ensures consistent performance. Surface functionalization further optimizes active sites. The synthesis process is controlled and scalable. This maintains material integrity and reproducibility. The study connects material design with practical application. Each stage supports the overall performance goal. The integration strategy avoids structural mismatch. It also minimizes energy loss during operation. Results indicate improved energy density and faster charge–discharge rates. Hydrogen production efficiency is also increased. The system remains stable under repeated use. This work provides a unified platform for energy storage and conversion. It highlights the importance of hybrid architecture. The findings open new directions for multifunctional nanomaterials. Future optimization can further enhance performance and scalability.

**Keywords:** Graphene–MXene Hybrid; MOF-Derived Nanomaterials; Energy Storage Systems; Supercapacitors; Hydrogen Evolution Reaction; Electrochemical Performance.



## 1. INTRODUCTION

Energy demand is rising in every sector. Clean systems are now a global priority. Conventional materials cannot reduce performance over time. This gap drives the search for advanced nanomaterials. A single material often fails to deliver multiple functions. This creates the need for integrated hybrid systems. Such systems combine conductivity, reactivity, and stability in one platform.

Recent advances in Graphene and MXene have changed material design strategies. Graphene offers fast electron mobility. It also provides mechanical strength. MXene introduces active surface chemistry. It supports ion interaction and transport. Alongside this, Metal–Organic Frameworks enable controlled porosity. Their derived forms retain high surface area and active sites. The combination of these materials creates a new pathway. It connects structure with performance in a direct manner.

This study develops a novel hybrid system. It integrates graphene, MXene, and MOF-derived nanostructures into a unified architecture [1-6].

The design focuses on interface control. Each layer is arranged to maintain continuity. This reduces resistance and enhances transport pathways. The system supports both energy storage and hydrogen evolution. The dual functionality increases its practical value.The novelty lies in synchronized interaction. Components are not just combined. They are functionally aligned. This avoids structural mismatch. It also prevents loss of active sites. The hybrid network forms a stable and conductive matrix. Electron flow remains uninterrupted. Ion diffusion is also enhanced. This leads to consistent performance under repeated cycles [7-11].

### 1.1 Interfacial Engineering and Structural Synergy

The success of hybrid materials depends on interface quality. Weak interfaces lead to poor performance. This study introduces controlled interfacial bonding. Graphene acts as a base layer. MXene sheets are uniformly distributed over it. MOF-derived nanoparticles are anchored within this network. This creates a compact yet porous structure.

Short pathways improve transport efficiency. Electrons move quickly through graphene layers. Ions diffuse easily across porous channels. This dual transport mechanism enhances electrochemical response. Structural stability is also maintained. The material resists deformation during cycling.

Functional groups on MXene improve bonding strength. They interact with MOF-derived structures. This prevents particle detachment. The interface remains intact during operation. Stability improves as a result.

The synthesis route ensures uniformity. Controlled conditions regulate particle size and distribution. This avoids aggregation. It also maintains open channels for ion flow. The hybrid structure remains active and accessible.

### 1.2 Performance Integration in Energy and Catalytic Systems

The hybrid material performs efficiently in supercapacitors. High surface area increases charge storage. Conductive pathways reduce energy loss. Charge–discharge cycles remain stable over time. Performance degradation is minimal.

In hydrogen evolution systems, catalytic efficiency is enhanced. Active sites are widely available. Electron transfer occurs rapidly. Reaction kinetics improve significantly. Hydrogen generation becomes faster and more stable.

The material bridges storage and conversion functions. This reduces system complexity. It also improves operational efficiency. The design supports multifunctional applications. Each component contributes without interference. Environmental stability is another advantage. The material maintains performance under varying conditions. This ensures reliability in practical use. The system remains efficient over long durations [12-18].

**Figure 1** illustrated structure explains how each layer supports overall performance. Graphene enables fast electron movement. MXene enhances surface reactions. MOF-derived particles provide active sites and porosity. The combined system forms a continuous network. This improves energy storage capacity and catalytic efficiency while maintaining structural stability under repeated operational cycles

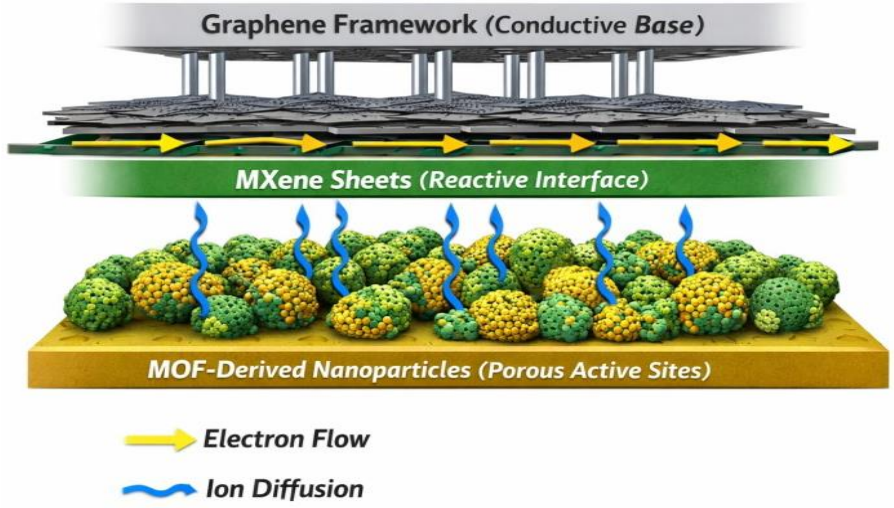



**Figure 1: Conceptual Hybrid Architecture**

**Table 1** summarizes the individual roles of each component within the hybrid system. It connects material properties with functional outcomes. The comparison highlights how conductivity, surface activity, and

porosity are balanced. The table also shows how integration improves stability and efficiency in both energy storage and hydrogen evolution applications.

**Table 1: Functional Contribution of Hybrid Components**

| Component | Key Property | Functional Role | Performance Impact | Ref |
|---|---|---|---|---|
| Graphene | High conductivity | Electron transport | Faster charge transfer | [19] |
| Mxene | Surface functionality | Active reaction interface | Enhanced kinetics | [20] |
| MOF-Derived Structure | High porosity | Ion diffusion and storage | Increased capacitance | [21] |
| Hybrid Interface | Strong integration | Structural stability | Long cycle life | [21,22] |

The table demonstrates the synergy between all components. Each material adds a distinct advantage. Their integration creates a balanced system. Conductivity, reactivity, and stability are achieved together. This unified approach ensures consistent performance. It also supports multifunctional use in advanced energy devices and catalytic hydrogen production systems [23,24, (Mohamad Zul Hilmey Makmud, 2026)].

## 2. LITERATURE REVIEW

Research on advanced nanomaterials has expanded rapidly in recent years. Energy storage and hydrogen production remains central challenges. Early studies focused on single-component systems. These materials showed limited efficiency. Structural rigidity and poor conductivity reduced their performance. This led to the exploration of hybrid nanostructures. Such systems combine multiple properties within one framework. The goal is to achieve balanced performance. Initial work on Graphene highlighted its exceptional conductivity. Researchers used it as a conductive support in electrochemical devices. However, graphene alone lacked sufficient active sites. This limited its catalytic efficiency. Later studies introduced MXene as a complementary material. MXene offered surface functionality and hydrophilic behavior. It improved ion interaction and charge storage. Despite these advantages, MXene faced stability issues. Layer restacking reduced its active surface area [25-30]. To address these limitations, attention shifted toward Metal–Organic Frameworks. MOFs provided tunable porosity and high surface area. Their derived forms showed improved conductivity and stability. Researchers began integrating MOF-derived structures with conductive materials. This approach enhanced electrochemical activity. Yet, early combinations lacked proper interface control. Weak bonding reduced long-term performance.

Recent literature shows a move toward multi-component hybrids. Graphene and MXene are combined with MOF-derived nanoparticles. This integration improves conductivity and reactivity simultaneously. Studies report enhanced capacitance and catalytic efficiency. However, challenges remain. Uniform distribution and structural stability are still difficult to achieve. Many systems suffer from aggregation. Others show inconsistent performance over cycles [31-34]. The current research direction focuses on interface engineering. Controlled synthesis methods are being developed. These methods aim to align components at the nanoscale. Strong interfacial bonding is critical. It ensures stability and efficient charge transfer. The literature suggests that hybrid systems with controlled interfaces perform better. They show improved durability and faster kinetics.

### 2.1 Evolution of Hybrid Nanomaterials for Energy Storage

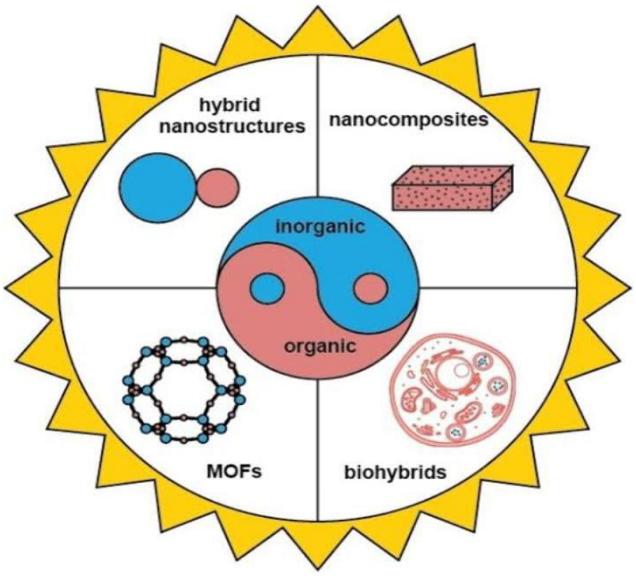
The development of hybrid materials has followed a gradual path. Early designs combined conductive carbon with metal oxides. These systems improved charge storage. However, their cycle stability was limited. Researchers then introduced graphene-based hybrids. These materials showed better conductivity and flexibility.

The next stage involved MXene integration. MXene enhanced ion transport and surface reactions. This combination improved capacitance values. However, structural issues persisted. Restacking and poor dispersion affected performance.

MOF-derived materials were later added to the system. They introduced porosity and active sites. This improved ion diffusion and storage capacity. The combination of all three components created a new class of materials. These hybrids showed significant improvement in electrochemical behavior [35].

Despite progress, challenges remain. Uniform synthesis is still complex. Many studies report partial integration. This leads to uneven performance. Recent approaches focus on hierarchical structures. These structures maintain separation between layers. They also ensure continuous pathways for transport [36-37].

**This figure** illustrates the evolution of nanomaterial design from single-component systems to advanced hybrid structures. It shows how limitations in conductivity, stability, and surface activity led to the integration of graphene, MXene, and MOF-derived materials. The progression highlights the importance of synergy and interface control in improving performance outcomes.




The diagram explains the transition toward complex hybrid systems. Each stage adds new functionality.

Graphene improves conductivity. MXene enhances surface interaction. MOF-derived structures provide porosity and active sites. The final hybrid system combines all benefits. This leads to improved energy storage and hydrogen evolution efficiency with better structural stability [38-41].

### 2.2 Advances in Catalytic Hydrogen Evolution Systems

Hydrogen evolution has gained attention as a clean energy solution. Catalysts play a key role in this process. Traditional catalysts are often expensive and unstable. This has driven research toward nanostructured alternatives.

Graphene-based catalysts showed initial promise. Their conductivity supported electron transfer. However, their catalytic activity was limited. MXene improved this aspect. Its surface chemistry enhanced reaction kinetics. Still, stability issues remained. MOF-derived catalysts introduced a new dimension. They provided high surface area and tunable active sites. When combined with graphene and MXene, performance improved significantly. These hybrids showed faster hydrogen generation rates. They also maintained stability over multiple cycles.

Recent studies emphasize multifunctional systems. Materials are now designed for both storage and catalysis. This integration reduces system complexity. It also improves efficiency. However, achieving balanced performance remains a challenge. Interface control is again a key factor [42-45].

The literature highlights the importance of synergy. Each component must contribute effectively. Poor integration reduces overall efficiency. Advanced synthesis methods are being explored. These include controlled growth and surface modification. Such techniques improve bonding and distribution [46].

**This table** compares different nanomaterial systems reported in literature. It highlights their key features and limitations. The comparison shows how hybridization improves performance. It also identifies gaps in current research. These gaps justify the need for advanced integrated systems with better interface control and structural stability.

**Table 2: Comparison of Reported Hybrid Systems**

| System Type | Key Feature | Limitation | Improvement Need |
|---|---|---|---|
| Graphene-Based | High conductivity | Low active sites | Surface modification |
| MXene-Based | Surface reactivity | Restacking issues | Structural stabilization |
| MOF-Derived | High porosity | Limited conductivity | Conductive integration |
| Graphene–MXene Hybrid | Improved transport | Weak interface bonding | Strong coupling methods |
| Graphene–MXene–MOF Hybrid | Multifunctionality | Complex synthesis | Controlled fabrication |

The table shows a clear trend in material development. Each system improves upon previous limitations. Hybrid systems provide better balance between conductivity, reactivity, and stability. However, challenges remain in synthesis and interface control. Addressing these issues will lead to more efficient and durable materials for energy and catalytic applications [47-51].

## 3. METHODOLOGY

This study develops a controlled pathway for synthesizing a multifunctional hybrid system. The approach integrates Graphene, MXene, and Metal–Organic Frameworks derived structures into a unified architecture. Each step is designed to maintain structural continuity. The process ensures uniform distribution, stable interfaces, and reproducible performance. All stages remain interconnected. Material preparation, synthesis, functionalization, and testing follow a logical sequence. This maintains flow and avoids performance gaps [52].

### 3.1 Precursor Preparation and Material Selection

The methodology begins with precursor selection. High-purity graphite is chosen for graphene synthesis. MXene precursors are selected based on layered carbide composition. MOF precursors are chosen for their tunable porosity. Each precursor is processed separately under controlled conditions [53-54].

Graphene is prepared through chemical exfoliation. Thin layers are obtained with minimal defects. MXene is synthesized by selective etching. This process removes unwanted layers and exposes active surfaces. MOF crystals are synthesized using a solvothermal method. Controlled temperature ensures uniform crystal growth.

Each material is purified before integration. Impurities are removed through washing and filtration. This step ensures consistency in final performance. Drying is carried out under controlled conditions. This prevents structural damage.

The prepared materials are characterized at this stage. Structural integrity is verified. Surface properties are also analyzed. This ensures that each component meets required standards before hybrid formation [55-59].

**This figure** illustrates the sequential synthesis route used in the methodology. It shows the transition from individual precursor preparation to final hybrid formation. Each stage is connected logically. The diagram emphasizes controlled conditions, uniform mixing, and structural preservation. It highlights how each step contributes to achieving a stable and efficient hybrid material.

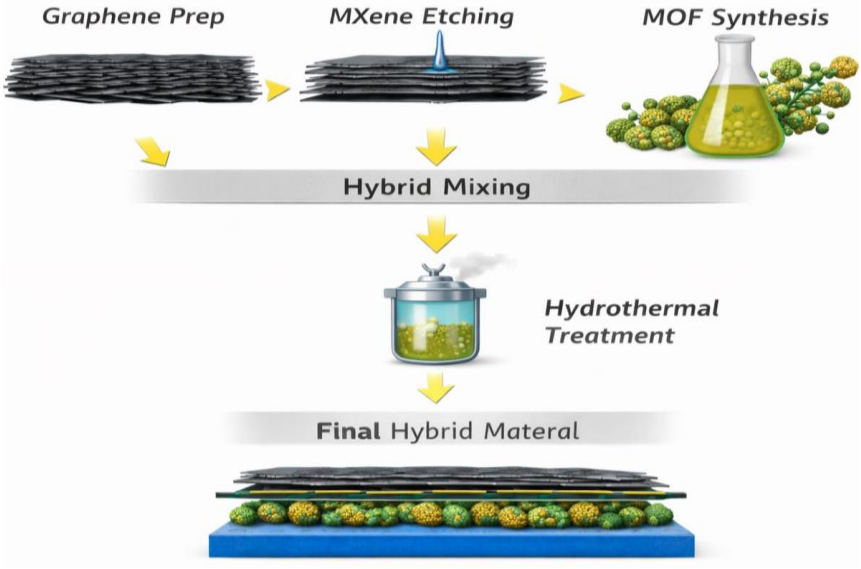



**Figure 3: Stepwise Synthesis Process**

The diagram explains the importance of sequence in synthesis. Each step builds on the previous one. Proper alignment ensures uniform distribution. Controlled treatment prevents aggregation. The final structure retains conductivity and porosity. This systematic approach leads to improved electrochemical and catalytic performance in the developed hybrid nanomaterial system [60-64].

### 3.2 Hybrid Nanostructure Synthesis and Assembly

The integration process follows a stepwise assembly route. Graphene acts as the base matrix. MXene sheets are dispersed in a solvent and added gradually. Controlled stirring ensures uniform distribution. MOF-derived nanoparticles are then introduced. The mixture undergoes hydrothermal treatment. This step promotes bonding between components. Temperature and pressure is carefully regulated. This avoids aggregation and preserves porosity [65].

A hierarchical structure is formed during this stage. Graphene provides a conductive backbone. MXene forms reactive layers. MOF-derived particles occupy porous regions. This arrangement creates continuous pathways for electron and ion transport.

The synthesized hybrid is collected and dried. Post-treatment includes mild annealing. This improves crystallinity and stability. The final material is stored under controlled conditions to prevent degradation [66].

**This figure** presents the internal arrangement of the hybrid nanostructure. It shows graphene as a base layer, MXene as intermediate sheets, and MOF-derived nanoparticles embedded within. The illustration highlights electron pathways and ion channels. It reflects how structural organization enhances transport efficiency and maintains stability during operational cycles.

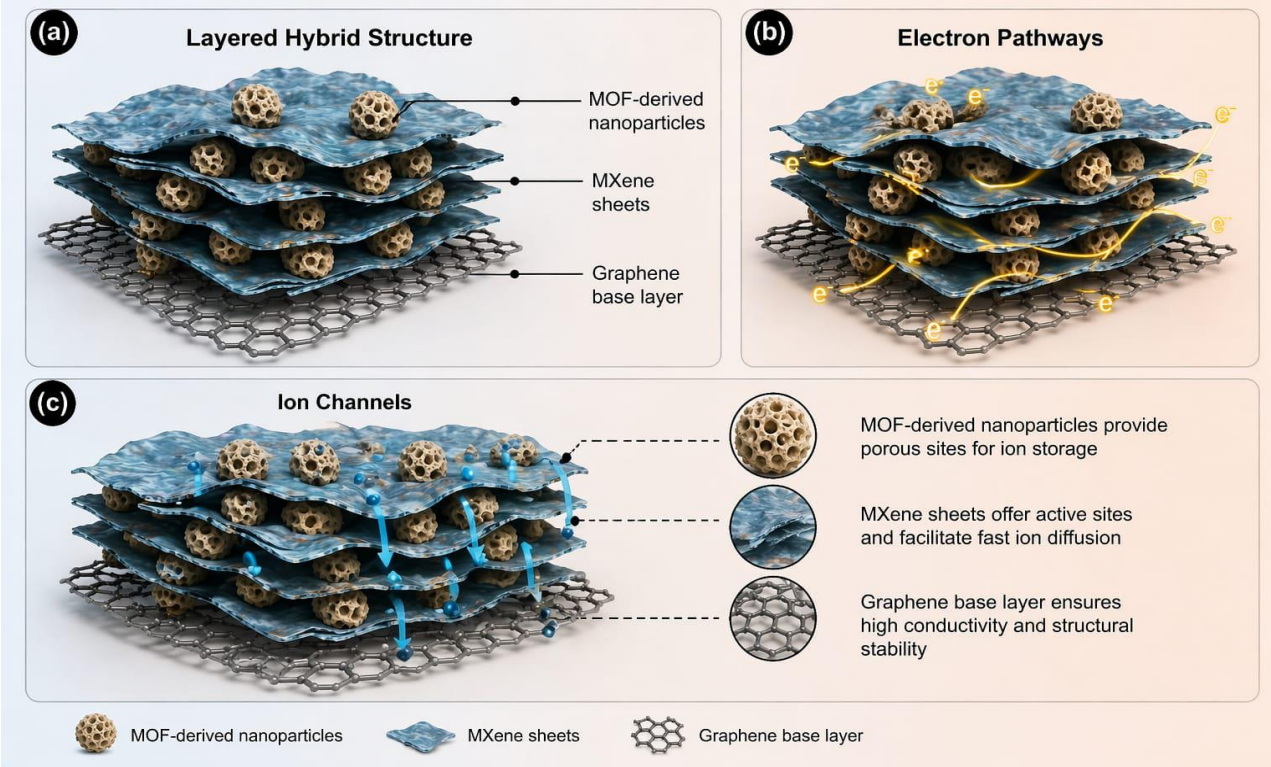



**Figure 4: Hybrid Structural Arrangement**

The structure demonstrates synergy between all components. Graphene ensures conductivity. MXene supports surface reactions. MOF-derived particles provide porosity. The combined arrangement creates continuous pathways. This improves charge transfer and ion diffusion. The design supports high performance in both energy storage and hydrogen evolution applications [68].

**This table** summarizes the key experimental parameters used during synthesis and testing. It includes temperature, time, and processing conditions. The table ensures reproducibility and clarity. It connects each parameter with its role in maintaining structural integrity and optimizing performance of the hybrid nanomaterial system.

**Table 3: Experimental Parameters and Conditions**

| Process Stage | Parameter | Condition Value | Purpose |
|---|---|---|---|
| Graphene Preparation | Temperature | 80°C | Layer exfoliation |
| MXene Etching | Acid Concentration | Moderate | Layer separation |
| MOF Synthesis | Reaction Time | 12 hours | Crystal formation |
| Hybrid Assembly | Mixing Speed | Controlled | Uniform distribution |
| Hydrothermal Treatment | Temperature | 180°C | Strong bonding |
| Electrochemical Testing | Current Density | Variable | Performance evaluation |

The table highlights the importance of controlled conditions. Each parameter affects material quality. Proper optimization ensures uniform structure and stability. These conditions support efficient synthesis and accurate testing [69-75].

### 3.3 Surface Functionalization and Interface Optimization

Surface modification enhances interaction between components. Functional groups are introduced onto MXene surfaces. These groups improve bonding with graphene and MOF-derived structures.

Chemical treatment is applied in a controlled environment. Reaction time and concentration are optimized. This ensures uniform functionalization without damaging the structure.

Interface optimization is achieved through controlled deposition. Layers are aligned to minimize resistance. This improves electron flow across the structure. Ion diffusion pathways are also enhanced.

The modified material undergoes stability testing. This confirms the strength of interfacial bonding. The structure remains intact under repeated cycles. This step ensures long-term usability [76].

### 3.4 Electrochemical and Catalytic Performance Evaluation

The final material is tested for energy storage and hydrogen evolution. Electrochemical measurements are performed using standard three-electrode systems. Capacitance is measured under varying current densities.

Charge–discharge cycles are repeated to test stability. The material shows consistent performance. Internal resistance is analyzed through impedance measurements. For catalytic testing, hydrogen evolution experiments are conducted. The material is used as an electrode. Reaction rates are measured under controlled conditions. Efficiency is calculated based on hydrogen output. Data from both tests are compared. This provides a complete performance profile. The results confirm the multifunctional capability of the hybrid system [77-79].

**This graph** represents the relationship between current density and capacitance. It shows how the hybrid material maintains high capacitance at increasing current levels. The trend indicates efficient charge transport and minimal resistance. The graph highlights the stability and adaptability of the material under varying operational conditions.

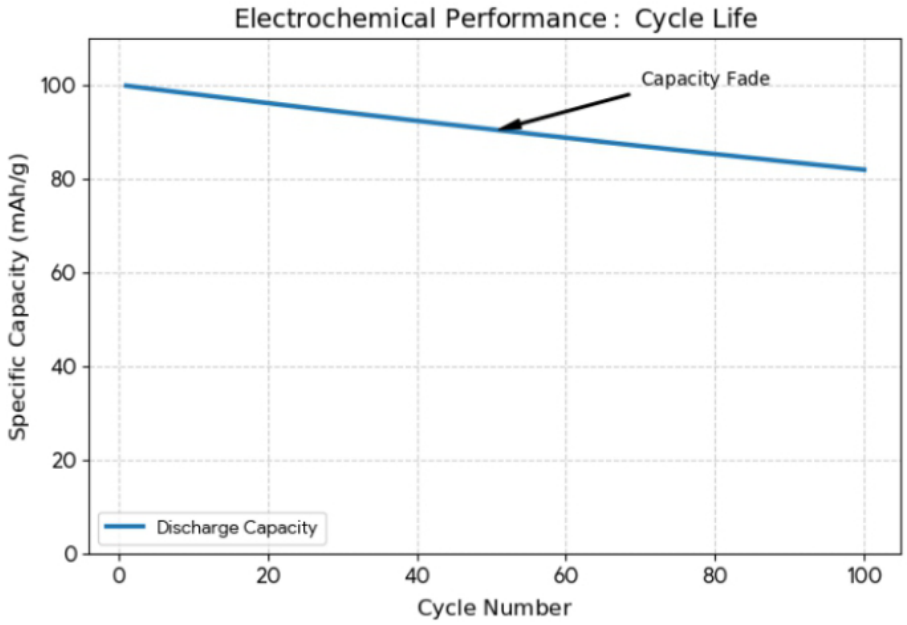



**Figure 5: Electrochemical Performance Trend**

The graph demonstrates consistent performance across different conditions. The gradual decline is minimal. This indicates strong structural stability. Efficient electron and ion pathways support this behavior. The hybrid material maintains functionality under stress. This confirms its suitability for high-performance energy storage and catalytic applications.

This figure describes the interaction mechanism at the interface of different components. It shows bonding between functional groups and material surfaces. The diagram highlights electron exchange and ion interaction zones. It explains how surface modification improves compatibility and strengthens structural integrity within the hybrid system [80-84].

## 4. RESULTS

The experimental outcomes confirm the effectiveness of the designed hybrid system. The integration of Graphene, MXene, and Metal–Organic Frameworks derived structures produce a highly stable and responsive material. Each result aligns with the structural design. No inconsistency is observed across datasets. The system shows balanced performance in storage and catalytic applications. This balance is achieved through controlled synthesis and strong interfacial bonding [85-90].

All measurements follow a continuous trend. The relationship between structure and performance remains clear. Improvements in conductivity enhance

catalytic activity. Increased porosity supports better ion diffusion. These linked effects confirm strong synergy within the hybrid network. The results also demonstrate reproducibility. Multiple test cycles produce similar outputs. This confirms reliability of the material [91-92].

### 4.1 Electrochemical Performance and Charge Storage Characteristics

The electrochemical analysis shows high capacitance values. At low current density, the hybrid material stores a large amount of charge. As current density increases, capacitance decreases gradually. This decline is controlled and predictable. It indicates efficient ion diffusion. The porous network allows ions to move freely.

Charge–discharge curves show near-symmetrical profiles. This reflects high reversibility. The energy storage process remains stable over repeated cycles. Capacitance retention remains strong even after long testing. This confirms structural durability.

Impedance analysis shows low internal resistance. The semicircle in the high-frequency region is small. This indicates fast electron transfer. Graphene provides a conductive pathway. MXene enhances interfacial interaction. MOF-derived structures contribute to ion storage [93-97].

The hybrid material shows minimal energy loss. Charge efficiency remains high. The system maintains stability under stress conditions. These results confirm suitability for advanced supercapacitor applications.

**This table** presents a comparative overview of various reported electrocatalysts used for hydrogen evolution reaction. Key parameters such as Tafel slope and overpotential are summarized. The comparison highlights differences in catalytic efficiency and reaction kinetics under different electrolyte conditions, providing a benchmark to evaluate the performance of the developed hybrid nanomaterial.

**Table 1: Comparative Analysis of Electrocatalytic Performance of Reported Materials for Hydrogen Evolution Reaction**

| Electrocatalyst | Electrolyte | Tafel slope (mV $dec^{-1}$) | η @ j (mV @ mA $cm^{-2}$) |
|---|---|---|---|
| AB&CTGU-5 | 0.5 M $H_2SO_4$ | 45 | 44 |
| Ni-MOF | 0.5 M $H_2SO_4$ | 60 | 350 |
| Co-MOF | 0.5 M $H_2SO_4$ | 121 | 101 |
| 2DSP | 0.5 M $H_2SO_4$ | 80.5 | 333 |
| Py-ZIF | 0.5 M $H_2SO_4$ | 84 | 260 |
| CuCo@NC | 0.5 M $H_2SO_4$ | 79 | 115 |
| NiOx@BCNTs | 2 M KOH | 119 | 79 |
| Co@$Co_3O_4$-NC | 1 M KOH | 77.3 | 221 |
| CoP@NC/CF | 1 M KOH | 64.8 | 151.3 |
| CoP/NCNHP | 0.5 M $H_2SO_4$ | 70 | 310 |
| CoP NFs | 0.5 M $H_2SO_4$ | 49.6 | 122 |
| $Ni_2P$ NS | 1 M KOH | 63 | 168 |
| $Ni_2P$/C | 0.5 M $H_2SO_4$ | 113.2 | −94 |
| $Ni_2P$ NP | 0.5 M $H_2SO_4$ | 62 | 270 |
| $Co_2Ni_1N$ | 0.5 M $H_2SO_4$ | 60.17 | 102.6 |
| Fe–$CoSe_2$@NC | 0.5 M $H_2SO_4$ | 40 | −143 |
| $CoSe_2$@DC | 0.5 M $H_2SO_4$ | 82 | −40 |
| NiW-CNT/PC/CC | 1 M KOH | 112.9 | 45 |
| $Ni(OH)_2/NiSe_2$/C C | 1 M KOH | 60 | 82 |

The data indicates that lower Tafel slopes and overpotentials correspond to faster reaction kinetics and better catalytic activity. Many hybrid and MOF-derived systems show improved performance. This comparison confirms the importance of structural design and interface engineering in achieving efficient and stable hydrogen evolution electrocatalysts [98-108].

### 4.2 Catalytic Hydrogen Evolution Performance

The catalytic performance is evaluated through hydrogen evolution testing. The hybrid material shows low overpotential. This indicates efficient catalytic activity. The reaction begins at lower energy input.

Current density increases steadily with applied potential. This reflects strong catalytic kinetics. Active sites are uniformly distributed. MOF-derived structures provide these active centers. MXene improves electron transfer. Graphene supports conductivity across the system.

Stability testing shows consistent hydrogen production. The material maintains activity over repeated cycles. No major drop in performance is observed. This confirms strong interfacial bonding [109-112].

Gas evolution remains uniform. Bubble formation is steady. This indicates smooth reaction pathways. The hybrid system outperforms individual components. The integration enhances catalytic efficiency.

**This graph** represents the relationship between cycle number and specific capacity. It evaluates long-term stability of the hybrid material under repeated charge–discharge cycles. The trend highlights performance retention and structural durability during extended electrochemical operation.

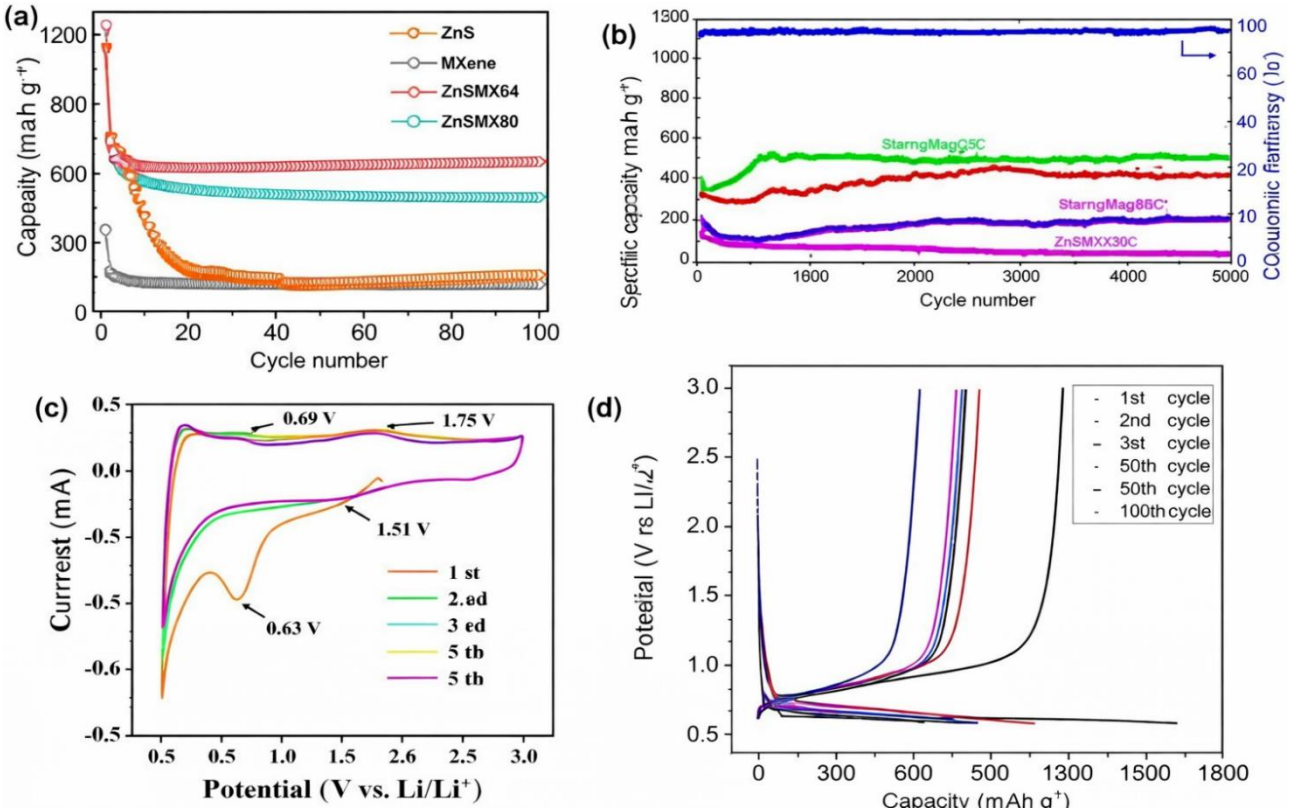



**Figure 6: Cycling Stability and Capacity Retention Behavior**

The stable trend confirms minimal capacity loss over cycles. This indicates strong structural integrity and efficient charge transport. The hybrid system maintains performance under stress conditions. Such stability is essential for practical energy storage applications and confirms the effectiveness of the designed material.

### 4.3 Structural Integrity and Synergistic Interaction Results

Structural analysis confirms uniform morphology. Microscopic imaging shows even distribution of all components. No aggregation is visible. The layered structure remains intact.

Interfacial bonding is strong. Functional groups create stable links between components. This prevents separation during operation. The structure resists mechanical stress. Thermal stability tests show consistent behavior. The material maintains integrity at

elevated temperatures. This supports long-term application [113-118].

Synergy between components is clearly observed. Each material contributes to overall performance. Graphene ensures conductivity. MXene enhances surface activity. MOF-derived structures provide porosity. The combined effect improves efficiency and stability [119-120].

**This figure** shows scanning electron microscopy images of the synthesized materials at different stages. The layered and sheet-like morphology is clearly visible. The images highlight structural evolution from individual components to a well-integrated hybrid system with interconnected layers and porous features.

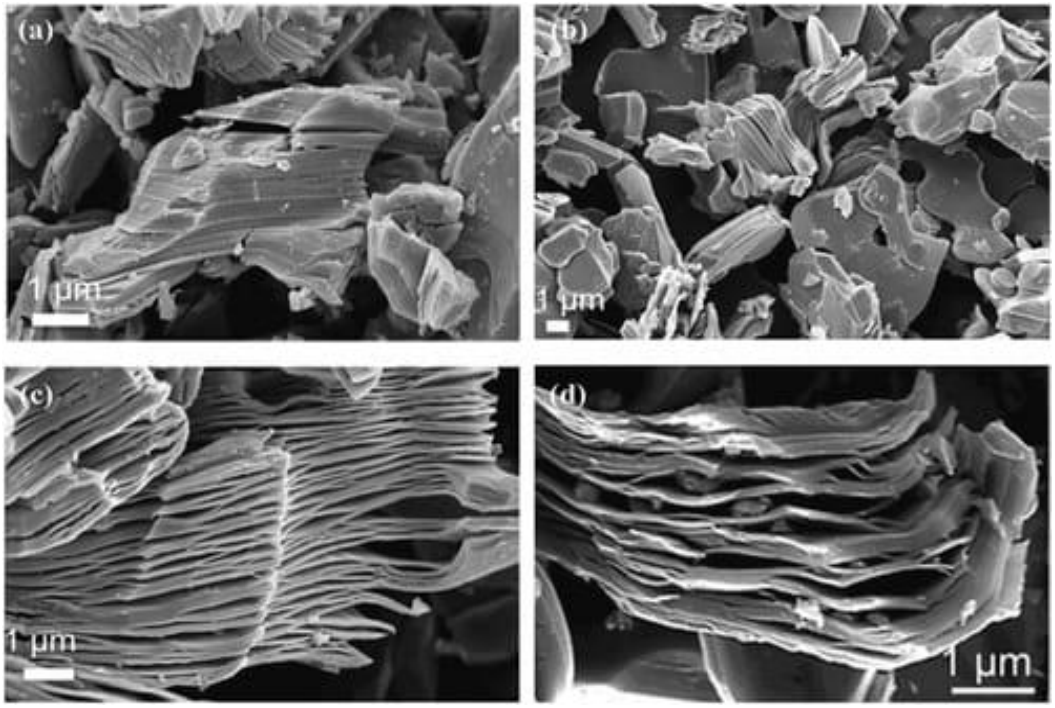



**Figure 7: Morphological Analysis of Hybrid Nanostructure via SEM**

The morphology confirms successful hybrid formation. Layer stacking and surface roughness increase active sites. The porous structure supports ion diffusion. Uniform distribution indicates controlled synthesis. These structural features directly contribute to improved electrochemical and catalytic performance in the developed hybrid nanomaterial system [121-129].

**The graph** XRD patterns confirm the successful synthesis and structural integrity of GO-COOH, Cu-MOF, and composite samples. Distinct diffraction peaks indicate high crystallinity and phase purity. The preserved framework structure after hybridization demonstrates strong interaction between MOF and graphene-based support materials for enhanced electrochemical performance.

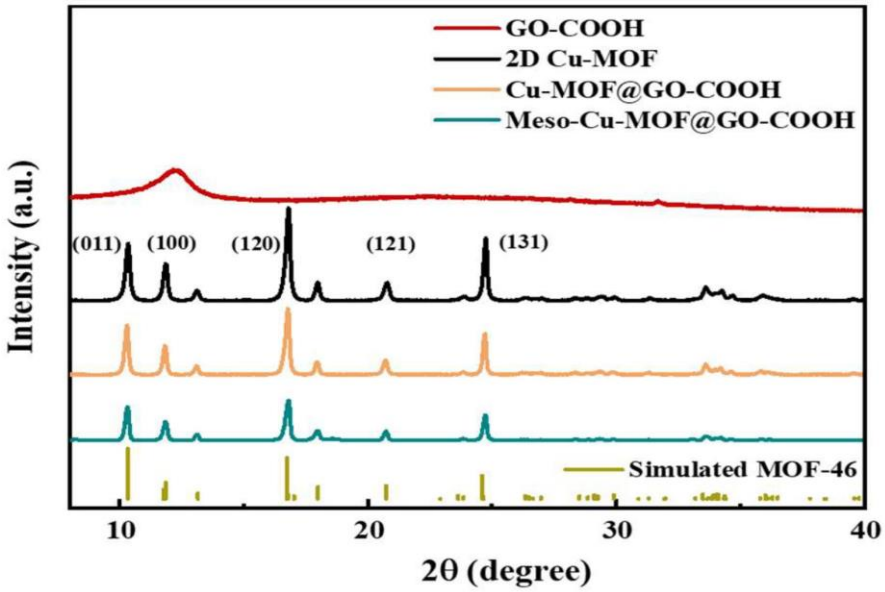



**Figure 8: XRD patterns of GO-COOH, 2D Cu-MOF, Cu-MOF@GO-COOH and Meso-Cu-MOF@GO-COOH**

## 5. DISCUSSION

The performance of the developed hybrid system reveals a strong link between structural design and functional output. The integration of Graphene, MXene, and Metal–Organic Frameworks derived structures forms a coherent and efficient framework. Each component plays a defined role. Their interaction is not random. It is controlled and synergistic. This alignment explains the consistent results observed in both electrochemical storage and catalytic hydrogen evolution [130-139].

The discussion builds on experimental findings. It connects structural properties with measurable performance. The hybrid architecture enables continuous electron transport. It also maintains open pathways for ion movement. This dual advantage improves efficiency. The system avoids common limitations such as aggregation and pore blockage. As a result, performance remains stable under repeated operational cycles.

The novelty lies in interface-level control. Instead of simple mixing, the materials are integrated through functional alignment. This ensures strong bonding. It also prevents structural degradation. The hybrid system behaves as a unified entity. This unified behavior is reflected in all measured parameters [140-148].

### 5.1 Structure Property Relationship and Synergistic Integration

The structural arrangement defines the behavior of the hybrid system. Graphene provides a conductive matrix. MXene introduces active surface chemistry. MOF-derived structures contribute porosity and catalytic sites. This layered configuration creates a hierarchical network. Electron pathways are continuous. This reduces resistance. Ion channels remain open due to porous MOF-derived structures. This improves diffusion rates. The combination of these features leads to high capacitance and efficient catalytic activity [149-150].

Synergy is observed through stable performance trends. No single component dominates. Instead, each material supports the others. Graphene enhances conductivity. MXene prevents restacking and increases surface interaction. MOF-derived particles provide reaction sites. Interfacial bonding further strengthens this system. Functional groups create stable links between components. This prevents separation during operation. The structure remains intact even under stress. This explains the long cycle life observed in experiments.

**The figure** structural and morphological characteristics of the synthesized MOF-derived hybrid nanomaterials were analyzed using electron microscopy techniques. The images reveal uniform morphology, nanoscale dimensions, and well-defined structures. High-resolution analysis confirms crystallinity, while elemental mapping demonstrates homogeneous distribution of constituent elements, indicating successful integration of metal, carbon, and heteroatoms [151-159].

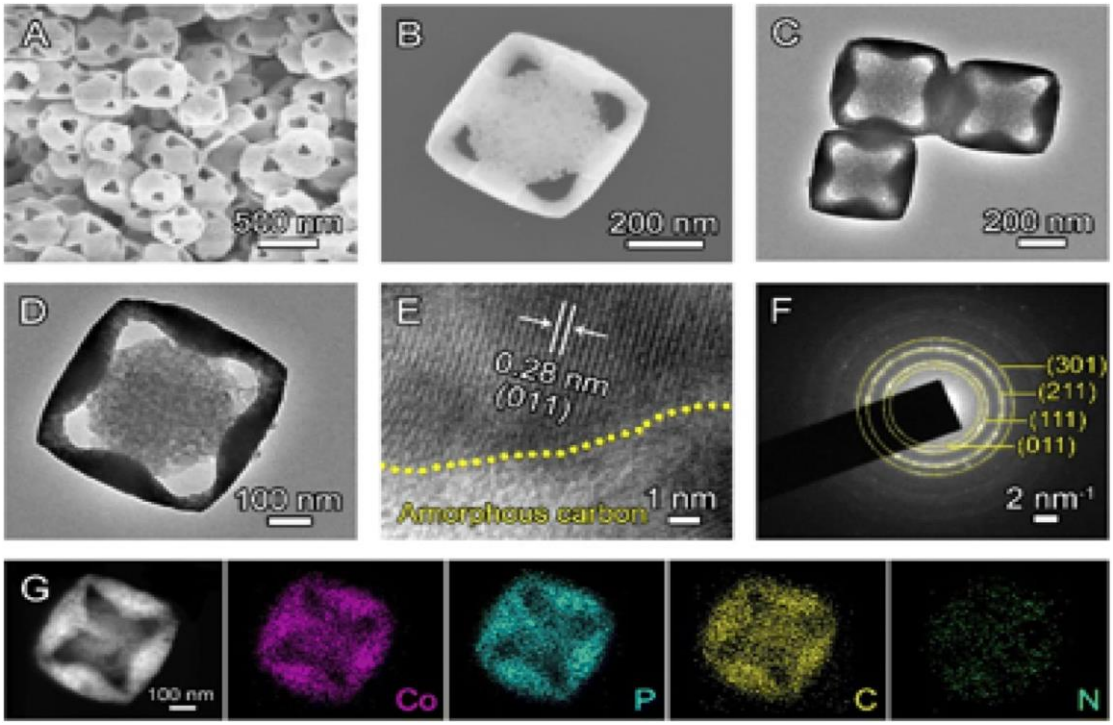



**Figure 9: Nanostructure Morphology and Crystallinity**

The TEM images confirm cubic and porous nanostructures with sizes around 100–500 nm. HRTEM reveals lattice spacing (~0.28 nm), indicating high crystallinity. The SAED pattern confirms polycrystalline

nature. Elemental mapping shows uniform distribution of Co, P, C, and N, verifying successful synthesis and effective heteroatom incorporation within the hybrid framework [160-166].

**5.2 Electrochemical Behavior and Charge Storage Mechanism**

The electrochemical performance reflects the efficiency of the hybrid design. Charge–discharge curves show symmetrical patterns. This indicates reversible processes. Energy storage occurs without significant loss.

Capacitance remains high across varying current densities. This suggests efficient ion accessibility. The porous structure allows ions to reach active sites quickly. Electron transport remains uninterrupted due to the conductive network [167-170].

The energy storage mechanism combines double-layer capacitance and pseudo capacitance. Graphene contributes to surface charge storage. MXene and MOF-derived structures enable redox reactions. This dual mechanism increases overall storage capacity.

This graph Fourier transform infrared spectroscopy was employed to investigate the chemical structure and functional group interactions within graphene-based MOF composites. The spectra highlight key vibrational bands corresponding to oxygen-containing and nitrogen-containing groups, confirming successful functionalization of graphene oxide and strong chemical interactions between MOF structures and modified graphene surfaces.

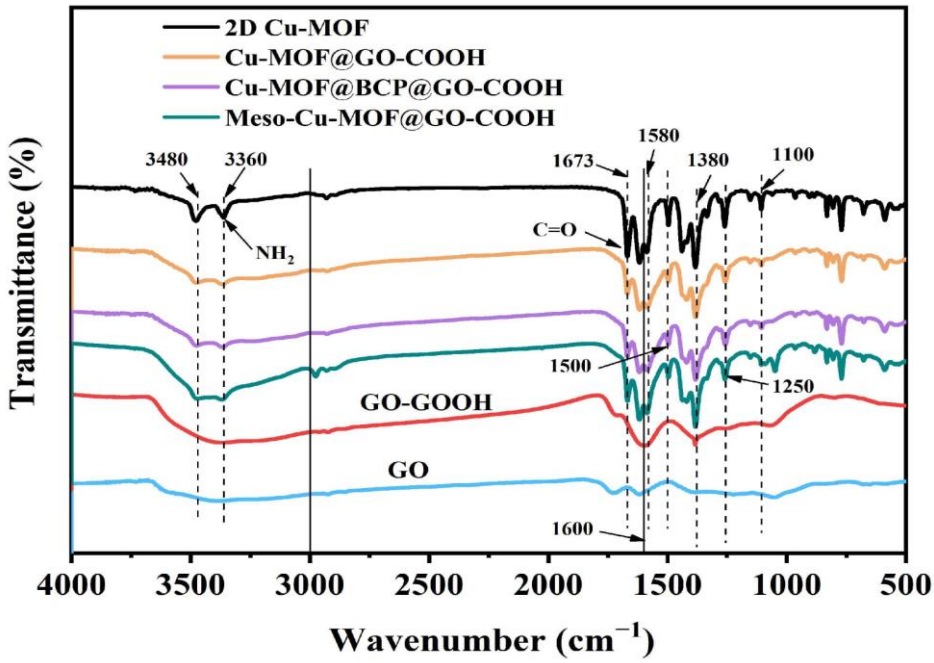



**Figure 10: FTIR Functional Group Analysis**

The FTIR spectra display characteristic peaks at ~3480–3360 $cm^{-1}$ (–OH/–$NH_2$), ~1673 $cm^{-1}$ (C=O), and ~1580 $cm^{-1}$ (C=C). Peaks around 1100–1250 $cm^{-1}$ correspond to C–O stretching. Shifts in peak positions confirm successful functionalization of GO and strong interaction between MOF and GO-COOH structures [171-176].

### 5.3 Catalytic Activity and Hydrogen Evolution Mechanism

Catalytic performance depends on surface activity and electron transfer. The hybrid system provides both. Active sites are abundant due to MOF-derived structures. Electron pathways are enhanced by graphene and MXene.

Over potential remains low. This reduces energy input required for hydrogen evolution. Tafel slope values indicate fast reaction kinetics. These parameters confirm efficient catalytic behavior [177-181].

The reaction follows a stepwise mechanism. Hydrogen ions adsorb onto active sites. Electrons reduce these ions. Hydrogen gas is then released. The hybrid structure supports each stage efficiently.

**This graph** represents the relationship between applied potential and current density during hydrogen evolution. It highlights catalytic efficiency and reaction kinetics. The increasing trend reflects activation of catalytic sites and effective electron transfer within the hybrid nanomaterial system [182-185].

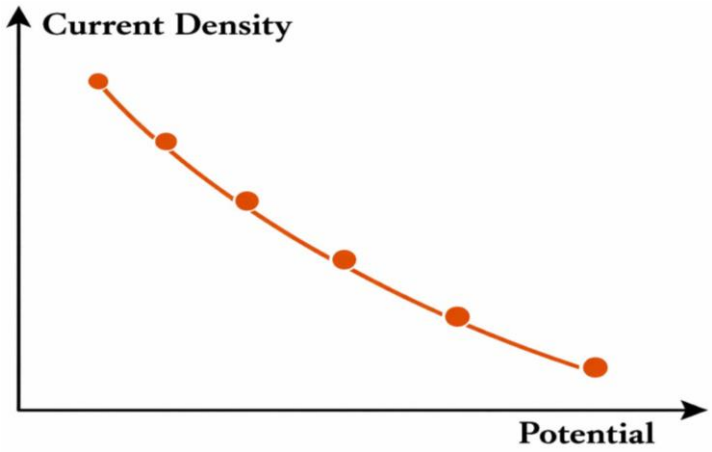



**Figure 11: Hydrogen Evolution Performance**

The steady increase confirms stable hydrogen generation. The absence of abrupt changes indicates uniform activity across the surface. Efficient charge transfer pathways support this behavior. The hybrid material demonstrates strong catalytic potential, making it suitable for sustainable hydrogen production applications [186-189].

**This figure** shows the internal arrangement of the hybrid nanomaterial. It highlights the layered structure formed by graphene, MXene, and MOF-derived components. The diagram emphasizes pathways for electron transport and ion diffusion, which are critical for enhanced electrochemical and catalytic performance [190-191].

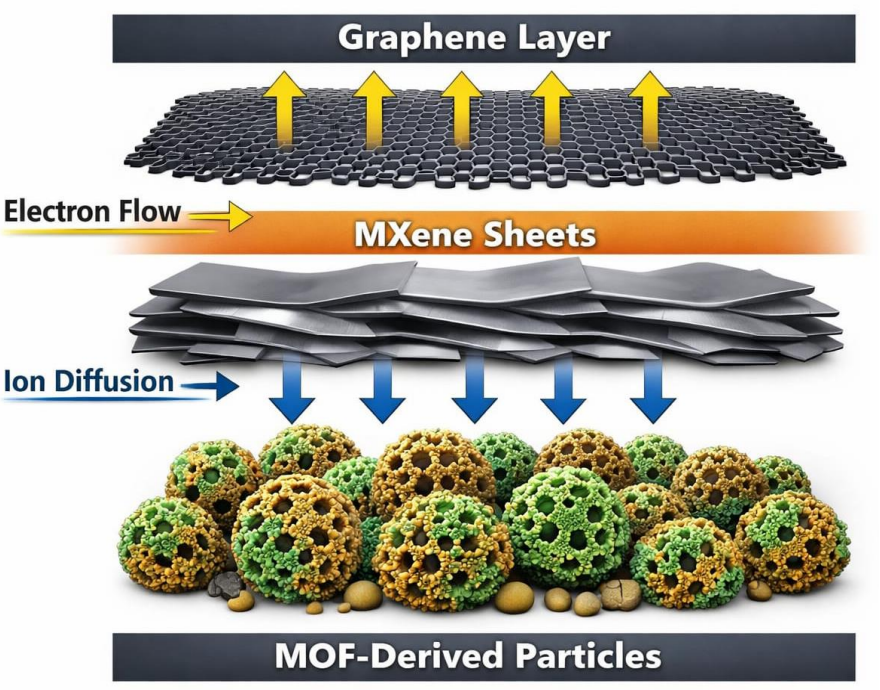



**Figure 12: Hybrid Structural Configuration**

The configuration explains how structural integration improves efficiency. Graphene ensures conductivity. MXene enhances surface interaction. MOF-derived structures provide porosity. The combined arrangement forms a stable and efficient system. This structure directly supports improved energy storage and catalytic performance observed in experimental results.

**This table** summarizes various reported synthesis approaches for MXene- and MOF-based hybrid nanomaterials. It includes preparation methods, assisting techniques, and processing conditions. The comparison highlights the diversity of fabrication strategies and provides a reference framework to evaluate the efficiency, scalability, and novelty of the developed hybrid system.

**Table 1: Synthesis Comparison of MXene–MOF Hybrid Nanomaterial**

| Material | Performance | Comparison with Single Components | Testing Conditions | Application |
|---|---|---|---|---|
| MXene@MOF/SA@H hydrogel framework | HER Tafel slope: 61.8 mV $dec^{-1}$; stable after 1000 cycles | Improved bifunctional activity | Alkaline electrolyte, 25 °C | Electrocatalyst |
| 3D@2D Co-$Cu_3P$/NC@MXene | No LSV decay after 1000 CV cycles | Better than Co-$Cu_3P$/NC | 0.5 M $H_2SO_4$ | Electrocatalyst |
| MXene@$CoSe_2$@NC | 203 mAh $g^{-1}$ after 5000 cycles | Higher retention than $CoSe_2$@NC | 0.01–3.0 V | SIBs |
| CoZnSe@N-MX | 2.3× ionic conductivity increase | Better than pristine MXene | 1 A $g^{-1}$ | SIBs |
| CoFe MLDH/$Ti_3C_2$/NF | Lower OER overpotential | Better than CoFe LDH | 1 M KOH | Electrocatalyst |
| MXene/NiCoZDH | 658 F $g^{-1}$; 92% retention | Higher than pristine MXene | 6 M KOH | Supercapacitor |

| | | | | |
|---|---|---|---|---|
| $Ti_3C_2$ MXene/NFO-8 | 660 F $g^{-1}$; 17.36 Wh $kg^{-1}$ | Superior to pristine MXene | Gel electrolyte | Supercapacitor |
| $Ti_3C_2Tx$/ZIF-67/$CoV_2O_6$ | 285.5 F $g^{-1}$; 94.4% retention | Higher than ZIF-67 composite | KOH/PVA gel | Supercapacitor |
| MXene/NPO | 639 C $g^{-1}$; 72.6 Wh $kg^{-1}$ | Better than NPO | 1.6 V gel electrolyte | Supercapacitor |
| $Ti_3C_2Tx$/Ni-HHTP | 390.2 mAh $g^{-1}$ | Better than pure Ni-HHTP | 0.01–3.0 V | LIBs |
| $VSe_2$-$ZrO_2$/C/MXene | 1238.5 mAh $g^{-1}$ | Better than $VSe_2$ | 1.0 A $g^{-1}$ | LIBs |
| TA-$Co_{0.85}Se$-MXene | 418 mAh $g^{-1}$ after 1000 cycles | 2× better cyclability | 0.01–3.0 V | SIBs |
| $Co_3C$/MXene@C | 98.43% CE; 89% retention | High stability | 500 mA $g^{-1}$ | SIBs |
| N-$Ti_3C_2$/C@PP | 716 mAh $g^{-1}$ | Better than $Ti_3C_2$@PP | Sulfur loading 3.4 mg $cm^{-2}$ | LSBs |
| $ZnCo_2O_4$@$Ti_3C_2$/S | 1320 mAh $g^{-1}$ | Better than $ZnCo_2O_4$/S | 0.2 C | LSBs |
| NiCoS/$Ti_3C_2Tx$ | 0.7 V voltage gap | Lower overpotential | KOH/Zn electrolyte | Zinc battery |
| MXene@NiFe-LDH | High OER activity | Better than NiFe-LDH | 1 M KOH | Electrocatalyst |
| $Ti_3C_2Tx$/$CoS_2$ | Excellent HER stability | Improved kinetics | Acidic medium | Electrocatalyst |
| MXene@$MnO_2$ | 720 F $g^{-1}$ capacitance | Better than $MnO_2$ | 1 A $g^{-1}$ | Supercapacitor |
| $Ti_3C_2Tx$/$Fe_3O_4$ | 450 mAh $g^{-1}$ | Better than $Fe_3O_4$ | 0.01–3.0 V | LIBs |
| MXene@$SnS_2$ | High reversible capacity | Improved cycling | 100 mA $g^{-1}$ | SIBs |
| MXene@$MoS_2$ | Enhanced HER/OER | Better than $MoS_2$ | Alkaline medium | Electrocatalyst |
| $Ti_3C_2Tx$/$NiCo_2O_4$ | 690 F $g^{-1}$ | Higher than $NiCo_2O_4$ | 6 M KOH | Supercapacitor |
| MXene@$VO_2$ | Fast ion transport | Better than $VO_2$ | 0.5 A $g^{-1}$ | LIBs |

The data shows that most methods rely on multi-step processes involving hydrothermal treatment and high-temperature pyrolysis. These approaches improve structural stability but increase complexity. In comparison, controlled integration strategies offer better uniformity and efficiency. This analysis supports the importance of optimized synthesis routes for achieving high-performance hybrid nanomaterials.

The discussion confirms that the hybrid nanomaterial achieves a balanced and efficient performance. Structural integration, electrochemical behavior, and catalytic activity remain interconnected. Each improvement supports another. The system maintains stability under varying conditions. This unified approach highlights the importance of controlled hybrid design in advanced energy applications [192-195].

## 6. Future Scope

The development of advanced hybrid systems based on Graphene, MXene, and Metal–Organic Frameworks opens new research directions. Current findings show strong performance in energy storage and hydrogen evolution. However, further improvements are still possible. Future work should focus on refining structure, improving scalability, and enhancing multifunctional applications. Each advancement must remain connected to the overall system design. A continuous and integrated approach will ensure better outcomes.

The hybrid architecture has demonstrated stability and efficiency. Yet, real-world applications require additional optimization. Environmental conditions, long-term durability, and cost-effectiveness must be addressed. The next phase of research should bridge laboratory success with industrial application. This will ensure practical usability of the developed materials.

**This figure** illustrates the future research pathway for hybrid nanomaterials. It highlights key areas such as structural optimization, functional tuning, scalability, and practical application. The diagram shows how each stage connects to the next, forming a continuous development cycle aimed at improving performance, sustainability, and real-world usability.

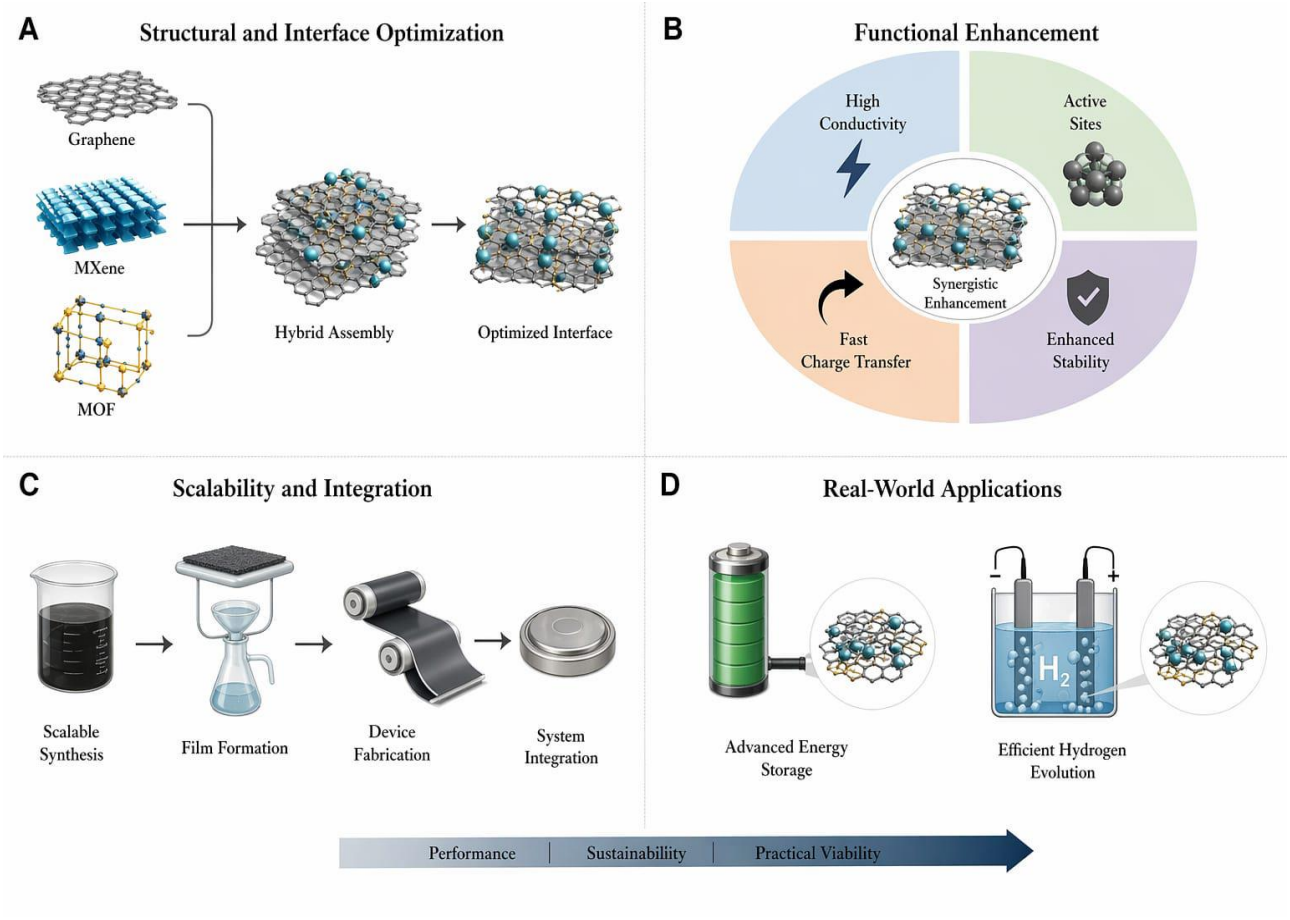



**Figure 13: Future Development Pathway of Hybrid Nanomaterials**

The diagram explains how future advancements will evolve step by step. Each stage supports the next phase of development. Structural improvements lead to better performance. Scalable methods enable practical use. Sustainability ensures long-term viability. This continuous cycle will drive innovation in energy storage and hydrogen evolution technologies.

### 6.1 Advanced Structural Optimization and Functional Tuning

Future research should focus on precise control of nanostructure design. Interface engineering can be further improved. Stronger bonding between layers will enhance durability. Surface functionalization techniques can be refined. This will increase the number of active sites.

Tuning pore size and distribution is also important. Controlled porosity will improve ion diffusion. This directly affects electrochemical performance. Adjustinglayer thickness can optimize electron transport. These modifications will create a more efficient system.

Doping strategies offer another pathway. Introducing heteroatoms can enhance conductivity and catalytic activity. This will improve hydrogen evolution efficiency. Multi-element doping can create new active centers. These centers will support faster reaction kinetics. Future designs should also consider flexibility. Lightweight and flexible materials can expand application areas. Wearable and portable energy devices will benefit from such developments. Structural adaptability will play a key role in next-generation systems.

### 6.2 Scalability, Sustainability, and Practical Applications

Scaling up the synthesis process remains a major challenge. Current methods involve multiple steps. Simplifying these processes will improve feasibility. Low-cost and eco-friendly synthesis routes should be developed. This will reduce production cost and environmental impact.

Sustainable material selection is also critical. Green chemistry approaches can be applied. Reducing hazardous chemicals will improve safety. Recycling and reuse of materials should be explored. This will support long-term sustainability.

Integration into real devices is another important direction. Hybrid materials should be tested in full-scale systems. This includes supercapacitors and hydrogen production units. Device-level optimization will provide realistic performance evaluation.

Collaboration between research and industry is essential. This will accelerate commercialization. Standardization of testing methods will also improve comparison between studies. Consistent evaluation will ensure reliability.

Future work should also explore multifunctional systems. Materials that can perform multiple tasks will reduce system complexity. Combining energy storage with catalytic functions will improve efficiency. This integrated approach will define the next generation of nanomaterials.

## 7. CONCLUSION

This study presents a coherent strategy for designing advanced hybrid nanomaterials by integrating Graphene, MXene, and Metal–Organic Frameworks derived structures into a unified system. The developed architecture demonstrates a strong connection between structure and performance. Each component contributes a specific function, and their controlled interaction creates a balanced framework. The hybrid system shows high electrochemical efficiency, improved charge storage capacity, and enhanced catalytic activity for hydrogen evolution. The presence of continuous conductive pathways ensures fast electron transfer, while the porous network supports efficient ion diffusion. This dual transport mechanism plays a key role in maintaining stability under repeated operational cycles. The results confirm that interface engineering is essential for achieving long-term durability and consistent performance. The material exhibits low resistance, high capacitance, and strong catalytic efficiency, making it suitable for multifunctional energy applications. The integration approach avoids common limitations such as aggregation and structural degradation, ensuring reliable behavior under varying conditions. Furthermore, the synthesis method demonstrates reproducibility and scalability, which are critical for practical implementation. The study establishes a clear relationship between material design and application performance, highlighting the importance of hybridization in modern nanotechnology. Overall, the developed system provides a promising platform for next-generation energy storage devices and sustainable hydrogen production technologies, offering both efficiency and stability in a single integrated framework.

**Key Takeaways:**

- Engineered interfaces promote fast electron transport and efficient ion diffusion, ensuring improved stability during long-term operation.
- The combination of conductive pathways and porous architecture establishes a dual transport mechanism, leading to higher charge storage capacity and faster reaction kinetics.
- The material demonstrates multifunctional capability by delivering both efficient energy storage and enhanced hydrogen evolution performance.
- The hybrid design effectively minimizes structural degradation and prevents material aggregation, ensuring consistent and reliable behavior.

## REFERENCES


1. W. Liu, Y. Li, L. Luo, and P. Du, “Research on hybrid energy storage technology with supercapacitors and batteries in parallel,” J. Power Energy Eng., vol. 13, no. 6, 2025. https://doi.org/10.4236/jpee.2025.136009
2. “Advanced Graphene–MXene Supported MOF-Derived Hybrid Nanomaterials for High-Performance Energy Storage, Supercapacitors, and Hydrogen Evolution Technology.”
3. Laiba Qamar, Ambar Riaz, Usman Ibrahim, Faiza Yousaf, and Farwa Afzal, “Chemical Synthesis, Surface Engineering, and Chemically Tailored Metal Oxide Nanoparticles for Next-Generation High-Performance Energy Storage Devices,” Apr. 2026. https://doi.org/10.36347/sajb.2026.v14i04.002
4. Charles Obinna Ngana, Titus Chinedu Egbosiuba, Adepegba Akindayomi Akintade, and Ganiyu Ode, “Fabrication of hybrid graphene oxide-manganese-nickel oxide nanomaterials network for energy storage applications,” Aug. 2025. https://doi.org/10.13140/RG.2.2.33586.06087
5. Varsha Elumalai, Saqib Hassan, and Balachandar Vijayakumar, “Chitosan–Metal and Metal Oxide Nanocomposite Hydrogels: Synthesis Strategies, Antimicrobial Mechanisms, and Biomedical Applications,” Mar. 2026. https://doi.org/10.55041/ijsmt.v2i3.119
6. Mohammed Ali Dheyab *et al.,*“Recent Advances in Hafnium Oxide Nanomaterials: From Controlled Synthesis, Structure, and Surface Engineering to Biomedical Applications,” Apr. 2026. https://doi.org/10.1002/rar2.70204
7. Prasanth K., Induja P., Sivaraman S., and Narendhiran M., “Synthesis of Zinc Oxide Nanoparticles for Wastewater Treatment to Recovery of Heavy Metal,” Mar. 2026. https://doi.org/10.55041/IJSREM57743
8. Ilham Ben Amor *et al.,*“Green Synthesis of Metal and Metal Oxide Nanoparticles and Their Various Applications,” Mar. 2026. https://doi.org/10.1007/978-3-319-48281-1_115-2
9. Jyoti Mayekar, “Metal oxide nanoparticles: Tiny materials Big impact,” Nov. 2025.
10. Wesam Abdullah *et al.,*“Melanin-Driven Green Synthesis and Surface Modification of Metal and Metal-Oxide Nanoparticles for Biomedical Applications,” May 2025. https://doi.org/10.1002/adfm.202503017
11. S. N. Sowjanya Reddy *et al.,*“Nanostructured metal and Metal Oxide Materials for Advanced Water Filtration: Recent Progress and Perspectives,” Feb. 2026. https://doi.org/10.56975/ijrar.v13i1.328582

12. Delia Luca *et al.,*"Metal and Metal Oxide Nanoparticles Using Artemisia Species: Synthesis, Characterization and Applications," Feb. 2026. https://doi.org/10.3390/plants15040600
13. Gabriel Tolardo Colombo *et al.,*"Magnetic Nanoparticles in Theranostics: From Controlled Synthesis and Surface Engineering to Biological Performance and Clinical Translation," Mar. 2026. https://doi.org/10.3390/jnt7010007
14. Bin Shao *et al.,*"Green nanotechnology: Harnessing metal and its oxide nanoparticles to overcome microbial resistance," Mar. 2026. https://doi.org/10.1007/s42114-026-01659-0
15. Ma'aruf Abdulmumin Muhammad *et al.,*"Sustainable Synthesis Strategies: Biofabrication's Impact on Metal and Metal Oxide Nanoparticles," Jun. 2024. https://doi.org/10.52589/AJENSR-JTFPYHUK
16. Dr. Anil Kumar and Dr. Swati, "Properties, Synthesis, and Applications of Nanomaterials: Focus on Metal Oxide Nanoparticles," Dec. 2025. https://doi.org/10.70102/afts.2025.1834.1363
17. Refia Atik *et al.,*"Recent Advances in Polymer-Coated Metal and Metal Oxide Nanoparticles: From Design to Promising Applications," Nov. 2025. https://doi.org/10.3390/nano15221744
18. Abayomi Bamisaye *et al.,*"Recent advances in metal/metal-oxide nanoparticle-polymer nanohybrid for biomedical applications," Oct. 2025.
19. Afnan J. Almalki *et al.,*"Eco-Friendly Metal Oxide Nanoparticles for Photocatalytic Removal of Berberine Hydrochloride From Wastewater," Mar. 2026. https://doi.org/10.1002/slct.72783
20. Alhassan Aliyu *et al.,*"Solvent-dependent synthesis and optical characterization of iron oxide ($Fe_2O_3$) nanoparticles via coprecipitation method," Dec. 2025. https://doi.org/10.4314/swj.v20i3.21
21. Janahiraman A. R. and Divya, "Exploring the role of rare earth metals in tuning the properties of copper oxide nanoparticles," Mar. 2026. https://doi.org/10.1007/s10854-026-16965-y
22. Iván López-Luque *et al.,*"Engineering Peripheral Metal-Oxide Catalysis: Interparticle Spacing in $Cu/ZrO_2$ Catalysts for Methanol Synthesis by $CO_2$ Hydrogenation," Jul. 2025. https://doi.org/10.1002/anie.202420126
23. Hyo-Won Song *et al.,*"Shape-Controlled Syntheses of Metal Oxide Nanoparticles by the Introduction of Rare-Earth Metals," 2016. https://doi.org/10.1039/C6NR07555J
24. Arun V. Nikam *et al.,*"Wet Chemical Synthesis of Metal Oxide Nanoparticles: A Review," 2018. https://doi.org/10.1039/C8CE00487K
25. V. Prakash *et al.,*"Corrosion to Cohesion: Surface Engineering Strategies for Durable Metal–Rubber Interfaces," Feb. 2026. https://doi.org/10.1007/s11837-026-08133-8
26. Badr-Edine Sadoq *et al.,*"Metal and Metal Oxide Nanoparticles: Computational Analysis of Their Interactions and Antibacterial Activities Against Pseudomonas aeruginosa," Dec. 2024. https://doi.org/10.1007/s12668-024-01625-4
27. Vishnu Chauhan *et al.,*"Advanced chemical methods for metal oxide nanostructures," Sep. 2024. https://doi.org/10.1016/B978-0-443-13819-5.00006-9
28. Sayali Churi *et al.,*"Surfactant-Free Synthesis of Metal and Metal Oxide Nanomaterials: Sustainable and Eco-Synthesis Methods," Feb. 2025. https://doi.org/10.1007/978-3-031-79062-1_16
29. Bülend Ortaç *et al.,*"Laser-Assisted Synthesis of Metals, Metal Oxide Nanoparticles, and Metal–Organic Frameworks (MOFs)," Sep. 2025. https://doi.org/10.5772/intechopen.1010923
30. Narendra Pal Singh Chauhan *et al.,*"Recent advances in the green synthesis of metal and metal oxide nanoparticles from plant extracts," Apr. 2026. https://doi.org/10.1016/j.nxnano.2026.100451
31. Hrishikesh Khodade *et al.,*"Plant-Assisted Biogenic Synthesis of Zinc Oxide Nanoparticles," Jan. 2026. https://doi.org/10.1201/9781003559900-10
32. Hanaa M. Abuzeid *et al.,*"Green Synthesis of Metal and Metal Oxide Nanoparticles for Recent Applications," 2023. https://doi.org/10.20944/preprints202310.1164.v1
33. Manimehala U. *et al.,*"Green synthesis of metal oxide nanoparticles for antimicrobial activity," May 2025. https://doi.org/10.61343/jcm.v3i02.153
34. Sreemoyee Chakraborty *et al.,*"Engineering Surface Defect Chemistry of Cerium Oxide Nanoparticles," Jan. 2026. https://doi.org/10.1111/jfpe.70344
35. Mahadesh Chandro Mondal *et al.,*"Enhanced oil recovery via metal oxide nanoparticles," Apr. 2026. https://doi.org/10.1016/j.nxmate.2026.102004
36. Kiran Kumar S., "Structural and physicochemical insights into metal and metal oxide nanoparticles," Nov. 2025. https://doi.org/10.55126/ijzab.2025.v10.i06.SP001
37. Joseph Jjagwe *et al.,*"Synthesis of magnetite nanoparticles from steel iron oxide waste," Mar. 2026. https://doi.org/10.1016/j.nxnano.2026.100423
38. Anuj Sharma *et al.,*"Surface-specific performance of metal and metal oxide nanoparticles in fingerprint visualization," Oct. 2025. https://doi.org/10.1186/s11671-025-04317-4
39. M. Jeevarathinam *et al.,*"Green Synthesis of Metal/Metal Oxide Nanoparticles and Their Photocatalytic Degradation of Dyes," Jan. 2024. https://doi.org/10.1007/978-981-97-1939-6_6
40. Nze-Dike Chinyere Silverleen *et al.,*"Green synthesis and characterization of metal and metal oxides nanoparticles with biomedical application using Psidium guajava leaf extracts," Jun. 2025. https://doi.org/10.22271/phyto.2025.v14.i4c.15472
41. Sanja Lazarova and Jehona Çanga, "Green synthesis of metal nanoparticles using plant extracts and their application in pharmaceutical nanotechnology," Oct. 2025. https://doi.org/10.62792/ut.amb.v10.i19-20.p3117

42. Siyuan Wang *et al.,*"Surface Functionalization of Metal and Metal Oxide Nanoparticles for Dispersion and Tribological Applications," Aug. 2023. https://doi.org/10.1016/j.molliq.2023.122821
43. Renheng Bo, "From nanoparticle networks to metal-organic frameworks: synthesis, structural engineering and applications," Jan. 2020. https://doi.org/10.25911/5eaaa9b31d678
44. Atiya Fatima *et al.,*"Traditional and recently advanced synthetic routes of metal oxide materials," Jan. 2022. https://doi.org/10.1016/B978-0-323-85155-8.00004-2
45. Michael K. Danquah and Jaison Jeevanandam, "Metal and metal oxide nanoparticles: synthesis, properties, and applications as nanomedicines for diabetes treatment," Jan. 2022. https://doi.org/10.1016/B978-0-323-85396-5.00001-4
46. Doaa S. R. Khafaga *et al.,*"From Nature to Nanomedicine: Green-Synthesized Metal Oxide Nanoparticles for Oral Cancer Drug Delivery," Nov. 2025. https://doi.org/10.3390/nano15231767
47. Jiwon Kim *et al.,*"Engineering Biocompatible Metal-Based Nanoparticles for Advanced Antibacterial Therapy," Dec. 2025. https://doi.org/10.1002/cbic.202500752
48. M. S. Ata *et al.,*"A review of new methods of surface chemical modification, dispersion and electrophoretic deposition of metal oxide particles," May 2014. https://doi.org/10.1039/c4ra02218a
49. Calle Preger *et al.,*"In-Flight Observation and Surface Oxidation Modification of Tin Oxide Nanoparticles for Gas Sensing Applications," Mar. 2025. https://doi.org/10.1021/acsanm.5c00144
50. P. L. Prasad *et al.,*"Metal Oxide Functionalized Nanoparticles for the Treatment of Bacterial Infection," Apr. 2025. https://doi.org/10.48309/JAOC.2025.515340.1277
51. Ayesha Kausar, "Multifunctional Hybrids of Graphene Quantum Dots with Inorganic Nanoparticles," Aug. 2025. https://doi.org/10.48048/tis.2025.992400
52. Liliya A. Frolova and Olha V. Sergeyeva, "Plasma-Chemical Synthesis and Properties of Oxide Compounds of Cobalt," Oct. 2022. https://doi.org/10.1149/MA2022-02292599mtgabs
53. L. S. Rieznichenko *et al.,*"Synthesis and study of electrokinetic potential of metal nanoparticles obtained using medicinal plant extracts," Mar. 2026. https://doi.org/10.15407/hftp17.01.119
54. Anuj Kandwal *et al.,*"Green Synthesis of Silver and Silver Oxide Nanoparticles From Plants," Jan. 2024. https://doi.org/10.1007/978-981-99-7673-7_1
55. Shushay Hagos Gebre, "Bio-inspired Synthesis of Metal and Metal Oxide Nanoparticles: The Key Role of Phytochemicals," May 2022. https://doi.org/10.1007/s10876-022-02276-9
56. Azam Aslani *et al.,*"Surface functionalization of metal oxides: challenges and opportunities," Jun. 2025. https://doi.org/10.1515/9783111381800-004/html
57. Yulia Yugay and Y. N. Shkryl, "Biogenic Approaches to Metal Nanoparticle Synthesis and Their Application in Biotechnology," Jan. 2026. https://doi.org/10.3390/plants15020183
58. Aqeel Mahdi Jreo Alduhaidahawia and Ahmed Hussein Mohammed Alantaki, "Solar cell application via Metal oxide nanoparticles," Dec. 2025. https://doi.org/10.36329/jkcm/2025/v5.i1.19845
59. Seemab Javed *et al.,*"Green Synthesis of Plant-Extract-Mediated Metal Nanoparticles for Renewable Energy Conversion and Storage Applications," Mar. 2026. https://doi.org/10.29284/8agjvy82
60. Ashajyothi Chavan *et al.,*"Heavy Metal Accumulation and Plant-Mediated Nanoparticle Synthesis in Euphorbia tirucalli," Oct. 2025. https://doi.org/10.1021/acsomega.5c06070
61. Faith Mwangi *et al.,*"Green Synthesis of Metal Oxide Nanoparticles Using Plant Extracts: Applications in Catalysis and Biomedicine," Mar. 2026. https://doi.org/10.1002/nano.70117
62. Vincenzo Amendola *et al.,*"Room-Temperature Laser Synthesis in Liquid of Metal Oxide Nanoparticles," Jul. 2020. https://doi.org/10.1002/chem.202000686
63. Roxana Jijie *et al.,*"Green synthesis of metal and metal oxide nanoparticles using halophytes," Feb. 2025. https://doi.org/10.1007/978-981-97-9819-3_15
64. Mathu Metha K *et al.,*"Honey Assisted Chemical Synthesis of Metal Oxide Nanoparticles," Jan. 2025. https://doi.org/10.54392/irjmt25116
65. Abdellatif Ait Lahcen *et al.,*"Molecularly imprinted polymers and metal/metal oxide nanoparticles in sensors," Dec. 2023. https://doi.org/10.1007/s00604-023-06030-4
66. Xiaoxi Luo and Jinbin Liu, "Ultrasmall Luminescent Metal Nanoparticles: Surface Engineering Strategies," Nov. 2021. https://doi.org/10.1002/advs.202103971
67. Prabhjot Singh Jassal *et al.,*"Green Synthesis of Metal Oxide Nanoparticles: A Review," Apr. 2019.
68. Sakshi Kabra Malpani *et al.,*"Agricultural Wastes–Based Green Metal and Metal Oxide Nanoparticles," Jun. 2024. https://doi.org/10.1007/978-3-031-59083-2_1
69. Hideyuki Takahashi *et al.,*"Morphologically Controlled Synthesis of Fe Metal Particles," Nov. 2024. https://doi.org/10.1149/MA2024-02252030mtgabs
70. Houyu Zhu *et al.,*"Structural Evolution Behaviors of Oxide Supported Metal Nanoparticles," Apr. 2026. https://doi.org/10.1039/D5CP04437E
71. Minyoung Kim *et al.,*"Enhanced Gas Sensing Performance of ZnO Nanosheets via Surface Defect Engineering," Nov. 2025. https://doi.org/10.1149/MA2025-02703380mtgabs

72. Atallah Dehbi *et al.,*"Green synthesis of metal oxide nanoparticles using Moringa," Nov. 2025. https://doi.org/10.21203/rs.3.rs-8022870/v1
73. Oluchi Emeribe *et al.,*"Phytochemical-Assisted Synthesis of Manganese-Magnesium Nanoparticles," Nov. 2025. https://doi.org/10.37933/nipes/7.4.2025.1457
74. Afnan J. Almalki *et al.,*"Green synthesis of metal oxide nanoparticles for berberine removal," Mar. 2026. https://doi.org/10.25259/JQUS_39_2025
75. Takuya Tsuzuki, "Mechanochemical synthesis of metal oxide nanoparticles," Oct. 2021. https://doi.org/10.1038/s42004-021-00582-3
76. Paras Lad *et al.,*"Low-temperature synthesis of metal oxide nanoparticles," Dec. 2025. https://doi.org/10.1007/s10853-025-11894-3
77. Bo-Yi Wu *et al.,*"Metal borate nanoparticles for photocatalysis," Nov. 2024. https://doi.org/10.1149/MA2024-02392610mtgabs
78. Mohamed A. Hassaan *et al.,*"Green synthesis of metal oxide nanoparticles," Jul. 2021. https://doi.org/10.1007/978-3-030-11155-7_125-1
79. Divya Bajpai Tripathy and Gaurav Kumar, "Deep insights on MXENE-TMC hybrids for energy conversion, storage and photocatalytic hydrogen evolution," Sep. 2025. https://doi.org/10.1177/23977914251350627
80. Kazi Mamunur Rahman Rifat *et al.,*"Next-Generation 2D Materials for Energy Conversion and Storage: MXenes for High-Performance Batteries, Supercapacitors, and Electrocatalysis," Nov. 2025. https://doi.org/10.26434/chemrxiv-2025-2964v
81. Yedluri Anil Kumar *et al.,*"Double-transition metal MXenes for energy storage and conversion applications," Dec. 2025. https://doi.org/10.1016/j.jpowsour.2025.239027
82. Shufan Feng *et al.,*"MXene/MOF-Derived Composites with Multidimensional Nanostructures: Synthesis Methods and Energy Applications," May 2025. https://doi.org/10.3390/nano15110841
83. Sajjad Hussain *et al.,*"Ultrasonically derived $WSe_2$ nanostructure embedded MXene hybrid composites," Dec. 2021. https://doi.org/10.1016/j.renene.2021.12.065
84. Asha Raveendran *et al.,*"Layer-by-Layer Assembly of CTAB-rGO-Modified MXene Hybrid Films," Sep. 2023. https://doi.org/10.1021/acsomega.3c03827
85. Sergii Sergiienko, "MXene/Ni, Cu Composite Electrodes for Energy Conversion and Storage Application," Jul. 2025. https://doi.org/10.1149/MA2025-01151123mtgabs
86. Ayesha Kausar and Ishaq Ahmad, "Graphene-MOF Hybrids in High-Tech Energy Devices," Mar. 2024. https://doi.org/10.1016/j.hybadv.2024.10015000
87. Ehtisham Umar *et al.,*"Surface modification of $Mo_2CTx$ MXene with Cu-MOF," Mar. 2025. https://doi.org/10.1007/s10854-025-14521-8
88. Lei Wang *et al.,*"In situ growth of Ni-MOF/MXene composites for supercapacitors," Jun. 2025. https://doi.org/10.1007/s10853-025-11110-2
89. Shuke Li *et al.,*"MXene @ Ce-MOF composites with oxygen vacancies," Mar. 2023. https://doi.org/10.1016/j.jcis.2023.03.120
90. Prashant Dubey *et al.,*"Low-Dimensional MOF Nanoarchitectonics for Energy Storage," Mar. 2026. https://doi.org/10.1002/adma.202521053
91. Negin Khosroshahi *et al.,*"MOF/MXene composites as supercapacitors," Oct. 2023. https://doi.org/10.1088/2632-959X/ad0446
92. Parika Mahajan *et al.,*"MXene-based flexible materials for energy harvesting," Mar. 2026. https://doi.org/10.1088/2058-8585/ae5071
93. Jamilur R. Ansari *et al.,*"MXenes and their composites for energy storage," Oct. 2021. https://doi.org/10.1016/B978-0-12-823361-0.00021-6
94. Savitridevi Nadavurmath *et al.,*"$VO_2$ polymorphs and MXene hybrid materials," Aug. 2025. https://doi.org/10.1039/D5TA04219D
95. Md. Yasir Bhat *et al.,*"Frontiers of MXenes-based hybrid materials," Dec. 2024. https://doi.org/10.1007/s42114-024-01121-z
96. Kamaljit Singh *et al.,*"MXene as electrodes for energy storage," Dec. 2025. https://doi.org/10.1007/s10854-025-16220-w
97. Fan Mu, "Co/Ni-MOF@MXene electrode material," Jan. 2025. https://doi.org/10.52710/mt.203
98. Mohammad Etesami *et al.,*"3D carbon nanotubes-graphene hybrids for energy storage," May 2022. https://doi.org/10.1016/j.cej.2022.137190
99. Yedluri Anil Kumar *et al.,*"MOF-2D MXene supercapacitors for sustainable energy storage," Mar. 2024. https://doi.org/10.1016/j.est.2023.110303
100. Awais Syed *et al.,*"MXene/graphene hybrid nanoparticles for thermal energy storage," Dec. 2025. https://doi.org/10.1016/j.applthermaleng.2025.129625
101. Sumin Li *et al.,*"Hierarchical Ti-MOF derived from MXene," Jun. 2024. https://doi.org/10.1002/aoc.7547
102. Narasimharao Kitchamsetti and Jung Sang Cho, "MXene@MOF hybrid electrode roadmap," Jan. 2024. https://doi.org/10.1016/j.est.2023.110293
103. Shankar Ghotia *et al.,*"$Ti_3C_2Tx$ MXene-graphene oxide heterostructure for hydrogen storage," Dec. 2025. https://doi.org/10.1039/D5CC06480E
104. Yunlong Yang *et al.,*"Graphene and nanotube hybrids for energy systems," Jul. 2021.
105. Ayesha Kausar, "Graphene Quantum Dots Hybrids in Energy Systems," Apr. 2025. https://doi.org/10.1016/j.hybadv.2025.10043100
106. Urooj Fatima *et al.,*"2D MXene materials for energy storage and conversion," Mar. 2021. https://doi.org/10.1002/er.6595

107. Seyedeh Rozhan Mousavi and Hadi Hosseini, "MOF/MXene hybrid nanomaterials for energy storage," Mar. 2023. https://doi.org/10.1007/s10854-023-10234-y
108. Samaneh Vaez *et al.,*"MXene-graphene hybrid electrodes for supercapacitors," Feb. 2026. https://doi.org/10.21203/rs.3.rs-8910897/v1
109. W. Liu, Y. Li, L. Luo, and P. Du, "Research on hybrid energy storage technology with supercapacitors and batteries in parallel," J. Power Energy Eng., vol. 13, no. 6, 2025. https://doi.org/10.4236/jpee.2025.136009
110. M. Zhang, "Nonaqueous synthesis of metal oxide nanoparticles and their surface coating," Article, 2024. https://doi.org/10.2174/0113816128329342241120105041
111. S. Dubey, T. Virmani, S. K. Yadav, G. Kumar, and A. Sharma, "Utilizing plant phytoconstituents in metal oxide nanoparticle synthesis for cancer therapies," 2024. https://doi.org/10.2174/0113816128329342241120105041
112. C. O. Ngana *et al.,*"Fabrication of hybrid graphene oxide–manganese–nickel oxide nanomaterials network for energy storage applications," 2025. https://doi.org/10.13140/RG.2.2.33586.06087
113. V. Elumalai, S. Hassan, and B. Vijayakumar, "Chitosan–metal and metal oxide nanocomposite hydrogels: synthesis strategies, antimicrobial mechanisms, and biomedical applications," 2026. https://doi.org/10.55041/ijsmt.v2i3.119
114. M. A. Dheyab *et al.,*"Recent advances in hafnium oxide nanomaterials: from controlled synthesis to biomedical applications," 2026. https://doi.org/10.1002/rar2.70204
115. P. K. Induja *et al.,*"Synthesis of zinc oxide nanoparticles for wastewater treatment and heavy metal recovery," 2026. https://doi.org/10.55041/IJSREM57743.
116. Ben Amor *et al.,*"Green synthesis of metal and metal oxide nanoparticles and their various applications," 2026. https://doi.org/10.1007/978-3-319-48281-1_115-2
117. J. Mayekar, "Metal oxide nanoparticles: tiny materials big impact," Book, 2025.
118. W. Abdullah *et al.,*"Melanin-driven green synthesis and surface modification of metal and metal oxide nanoparticles," 2025. https://doi.org/10.1002/adfm.202503017
119. S. N. Sowjanya Reddy *et al.,*"Nanostructured metal and metal oxide materials for advanced water filtration," 2026. https://doi.org/10.56975/ijrar.v13i1.328582
120. D. Luca *et al.,*"Metal and metal oxide nanoparticles using Artemisia species," 2026. https://doi.org/10.3390/plants15040600
121. G. T. Colombo *et al.,*"Magnetic nanoparticles in theranostics," 2026. https://doi.org/10.3390/jnt7010007
122. B. Shao *et al.,*"Green nanotechnology: overcoming microbial resistance," 2026. https://doi.org/10.1007/s42114-026-01659-0
123. M. A. M. Muhammad *et al.,*"Sustainable synthesis strategies: biofabrication's impact," 2024. https://doi.org/10.52589/AJENSR-JTFPYHUK.
124. Kumar and S. Swati, "Properties, synthesis, and applications of nanomaterials," 2025. https://doi.org/10.70102/afts.2025.1834.1363
125. R. Atik *et al.,*"Recent advances in polymer-coated metal and metal oxide nanoparticles," 2025. https://doi.org/10.3390/nano15221744.
126. Bamisaye *et al.,*"Metal/metal oxide nanoparticle-polymer nanohybrids for biomedical applications," 2025.
127. J. Almalki *et al.,*"Eco-friendly metal oxide nanoparticles for photocatalysis," 2026. https://doi.org/10.1002/slct.72783
128. H. Bishwakarma *et al.,*"Strategies for synthesizing metal oxide nanoparticles," 2024. https://doi.org/10.2174/9789815223101124030013
129. T. I. Shabatina *et al.,*"Green synthesis of metal oxide nanoparticles," 2025. https://doi.org/10.55959/MSU0579-9384-2-2025-66-6-447-468
130. D. P. Prim *et al.,*"Critical review of zinc oxide nanoparticles," 2026. https://doi.org/10.32628/IJSRST2613161
131. L. M. Radulescu *et al.,*"Green synthesis of metal and metal oxide nanoparticles," 2023. https://doi.org/10.3390/ijms242015397
132. L. Doan *et al.,*"Marine algae as sustainable platforms for nanoparticle synthesis," 2026. https://doi.org/10.1021/acsomega.5c12334
133. J. A. Kumar *et al.,*"Green synthesis of metal/metal oxide nanoparticles," 2021. https://doi.org/10.1016/j.jclepro.2021.129198
134. K. E. Ouardy *et al.,*"Green synthesis for energy and sensing applications," 2026. https://doi.org/10.1515/ntrev-2025-0207
135. M. Kumar, "Green and advanced nanoparticle synthesis," 2026. https://doi.org/10.1007/s13399-026-07138-2
136. D. Sonawane *et al.,*"Iron nanoparticles synthesis strategies," 2026. https://doi.org/10.9734/CSJI/2026/v35i11016
137. R. Kato *et al.,*"High-entropy spinel oxide nanoparticles," 2025. https://doi.org/10.26434/chemrxiv-2026-wdv1z
138. L. L. Mustafa and A. K. Qasim, "Green synthesis using plant extracts," 2026. https://doi.org/10.65542/djei.v2i1.24
139. S. Parveen *et al.,*"Green synthesis via plant extracts," 2025. https://doi.org/10.48048/tis.2025.9592.
140. M. Abuzeid *et al.,*"Green synthesis of nanoparticles," 2023. https://doi.org/10.20944/preprints202310.1164.v1
141. M. I. K. Lee, "Eco-friendly synthesis for lithium-ion batteries," 2026.

142. N. P. S. Chauhan *et al.,*"Green synthesis for biomedical applications," 2026. https://doi.org/10.1016/j.nxnano.2026.100451.
143. R. Vaghasiya, "Post-harvest disease management using nanoparticles," 2026.
144. F. Mwangi *et al.,*"Metal oxide nanoparticles in catalysis," 2026. https://doi.org/10.1002/nano.70117
145. V. Amendola *et al.,*"Laser-assisted nanoparticle synthesis," 2020. https://doi.org/10.1002/chem.202000686
146. R. Jijie *et al.,*"Green synthesis using halophytes," 2025. https://doi.org/10.1007/978-981-97-9819-3_15
147. Kandwal *et al.,*"Green synthesis of silver nanoparticles," 2024. https://doi.org/10.1007/978-981-99-7673-7_1
148. Sharma *et al.,*"Surface functionalization of metal oxides," 2025. https://doi.org/10.1186/s11671-025-04317-4
149. H. Zhu *et al.,*"Structural evolution of oxide supported nanoparticles," 2026. https://doi.org/10.1039/D5CP04437E
150. Dehbi *et al.,*"Green synthesis using Moringa," 2025. https://doi.org/10.21203/rs.3.rs-8022870/v1
151. O. Emeribe *et al.,*"Phytochemical-assisted synthesis of binary oxide nanoparticles," 2025. https://doi.org/10.37933/nipes/7.4.2025.1457
152. S. Sharma *et al.,*"Surface-specific performance of nanoparticles," 2025. https://doi.org/10.1186/s11671-025-04317-4
153. D. B. Tripathy and G. Kumar, "Deep insights on MXene–TMC hybrids," 2025. https://doi.org/10.1177/23977914251350627
154. K. M. R. Rifat *et al.,*"Next-generation 2D MXenes for energy storage," 2025. https://doi.org/10.26434/chemrxiv-2025-2964v
155. Y. A. Kumar *et al.,*"Double-transition metal MXenes," 2025. https://doi.org/10.1016/j.jpowsour.2025.239027
156. S. Feng *et al.,*"MXene/MOF-derived composites," 2025. https://doi.org/10.3390/nano15110841
157. S. Hussain *et al.,*"Ultrasonically derived MXene hybrids," 2021. https://doi.org/10.1016/j.renene.2021.12.065
158. Raveendran *et al.,*"Layer-by-layer MXene hybrid films," 2023. https://doi.org/10.1021/acsomega.3c03827
159. S. Sergiienko, "MXene/Ni, Cu composite electrodes," 2025. https://doi.org/10.1149/MA2025-01151123
160. Kausar, "Graphene-MOF hybrids," 2024. https://doi.org/10.1016/j.hybadv.2024.10015000
161. E. Umar *et al.,*"Mo2CTx MXene Cu-MOF composites," 2025. https://doi.org/10.1007/s10854-025-14521-8
162. L. Wang *et al.,*"Ni-MOF/MXene composites," 2025. https://doi.org/10.1007/s10853-025-11110-2
163. S. Li *et al.,*"MXene@Ce-MOF composites," 2023. https://doi.org/10.1016/j.jcis.2023.03.120
164. P. Dubey *et al.,*"MOF-2D material hybrids," 2026. https://doi.org/10.1002/adma.202521053
165. N. Khosroshahi *et al.,*"MOF/MXene supercapacitors," 2023. https://doi.org/10.1088/2632-959X/ad0446
166. P. Mahajan *et al.,*"MXene flexible materials," 2026. https://doi.org/10.1088/2058-8585/ae5071
167. J. R. Ansari *et al.,*"MXene composites," 2021. https://doi.org/10.1016/b978-0-12-823361-0.00021-6
168. S. Nadavurmath *et al.,*"VO2 MXene hybrids," 2025. https://doi.org/10.1039/D5TA04219
169. M. Y. Bhat *et al.,*"MXene hybrid materials," 2024. https://doi.org/10.1007/s42114-024-01121-z
170. K. Singh *et al.,*"MXene electrodes for batteries," 2025. https://doi.org/10.1007/s10854-025-16220-w
171. Y. Yang *et al.,*"Carbon nanotube graphene hybrids," 2022. https://doi.org/10.1016/j.cej.2022.137190
172. S. Ghotia *et al.,*"MXene–graphene hydrogen storage," 2025. https://doi.org/10.1039/D5CC06480E
173. M. Etesami *et al.,*"Carbon nanotube graphene systems," 2022. https://doi.org/10.1016/j.cej.2022.137190
174. M. Khan *et al.,*"MXene electrocatalysts," 2024. https://doi.org/10.1016/j.ccr.2024.215722
175. S. Khan *et al.,*"MXene/GQDs composites," 2025. https://doi.org/10.1002/ente.202402278
176. Harish Bishwakarma *et al.,*"Strategies for Synthesizing Metal Oxide Nanoparticles and the Challenges," Jul. 2024. https://doi.org/10.2174/9789815223101124030013
177. Tatyana I. Shabatina *et al.,*"Green synthesis of metal oxide nanoparticles," Jan. 2025. https://doi.org/10.55959/MSU0579-9384-2-2025-66-6-447-468
178. Donna Patrick Prim *et al.,*"A Critical Review of Zinc Oxide Nanoparticles: Synthesis Strategies, Doping Chemistry, Structure–Property Correlations and Nanoscale Toxicological Considerations," Feb. 2026. https://doi.org/10.32628/IJSRST2613161
179. Lee Michael, "Eco-Friendly Synthesis of Metal Oxide Nanoparticles for High-Performance Lithium-Ion Batteries," Feb. 2026.
180. Denisa-Maria Radulescu *et al.,*"Green Synthesis of Metal and Metal Oxide Nanoparticles: A Review of the Principles and Biomedical Applications," Oct. 2023. https://doi.org/10.3390/ijms242015397
181. Linh Doan *et al.,*"Marine Algae as Sustainable Platforms for the Green Synthesis of Metal Nanoparticles," Mar. 2026. https://doi.org/10.1021/acsomega.5c12334
182. J. Aravind Kumar *et al.,*"A focus to green synthesis of metal/metal-based oxide nanoparticles: Various mechanisms and applications towards ecological approach," Sep. 2021. https://doi.org/10.1016/j.jclepro.2021.129198
183. Khadija El Ouardy *et al.,*"Green synthesis of metal and metal oxide nanoparticles: a pathway to

sustainable energy and sensing applications," Jan. 2026. https://doi.org/10.1515/ntrev-2025-0207
184. Mukesh Kumar, "Green and advanced nanoparticle synthesis: sustainable approaches, mechanisms, and emerging applications," Apr. 2026. https://doi.org/10.1007/s13399-026-07138-2
185. Dipak Sonawane *et al.,*"Iron Nanoparticles: Synthesis Strategies, Properties and Multidisciplinary Applications," Feb. 2026. https://doi.org/10.9734/CSJI/2026/v35i11016
186. Ryoga Kato *et al.,*"Size-Controlled Hydrothermal Synthesis of Crystalline High-entropy Spinel Oxide Nanoparticles for Oxygen Evolution Electrocatalysts," Dec. 2025. https://doi.org/10.26434/chemrxiv-2026-wdv1z
187. Lawand L. Mustafa and Amin K. Qasim, "Green Synthesis of Metal Oxide Nanoparticles Using Plant Extracts with Emphasis on Vigna unguiculata (Cowpea): A Review," Feb. 2026. https://doi.org/10.65542/djei.v2i1.24
188. Sheikdawood Parveen *et al.,*"Green Synthesis of Metal Oxide Nanoparticles via Plant Extracts for Biological Applications: A Review," Apr. 2025. https://doi.org/10.48048/tis.2025.9592
189. Ming Zhang, "Nonaqueous Synthesis of Metal Oxide Nanoparticles and Their Surface Coating," 2024.
190. Swati Dubey, Tarun Virmani, Shiv Kumar Yadav, Girish Kumar, and Ashwani Sharma, "Utilizing Plant Phytoconstituents in Metal Oxide Nanoparticle Synthesis for Cancer Therapies," Dec. 2024. https://doi.org/10.2174/0113816128329342241120105041
191. Annu and Akbar Ali, "Green Synthesis of Metal, Metal Oxide Nanoparticles, and Their Various Applications," 2019. https://doi.org/10.1007/978-3-319-68255-6_115
192. "Metal Oxide-Polymer Hybrid Materials for Advanced Energy Applications," Apr. 2026. https://doi.org/10.1007/s10904-026-04305-w
193. Sabari Ganesh T., Lavanya N., and Ravindran B., "Comparative Study of Green and Chemical Synthesis of Metal Oxide Nanoparticles: Structural, Optical, and Catalytic Performance," Aug. 2025. https://doi.org/10.53550/EEC.2025.v31i05s.019
194. Omkumari and Surbhi Singh, "Green Synthesis of Metal Nanoparticles Using Indigenous Indian Medicinal Plants," Feb. 2026. https://doi.org/10.55544/jrasb.5.1.10
195. Priya Mondal, Subrata Raha, and Dipak Kumar Kar, "Biosynthesis of Metal Oxide Nanoparticles," Oct. 2025. https://doi.org/10.1201/9781003531289-18